Multimed Tools Appl (2018) 77:3125–3141
DOI 10.1007/s11042-017-4954-9

Nighttime image Dehazing with modified models of color transfer and guided image filter

Bo Jiang[1] · **Hongqi Meng**[1] · **Xiaolei Ma**[2] · **Lin Wang**[1] · **Yan Zhou**[1] · **Pengfei Xu**[1] · **Siyu Jiang**[3] · **Xianjia Meng**[1]

Received: 21 February 2017 / Revised: 4 May 2017 / Accepted: 15 June 2017 /
Published online: 23 July 2017

Abstract Taking into account of the illumination characteristics of nighttime imaging, a new method for nighttime image dehazing is proposed in this paper. In the first place, based on the color transfer theory, the illumination level of nighttime hazy image can be artificially enhanced through flexibly selecting the reference image. In contrast to the classical model of color transfer with the strategy of overall to overall transfer, the modified model focuses on the different characteristics of various regions in the original image, and it works well even though the nighttime image is interfered by various artificial light sources. In the second place, the enhancement dehazing method based on the theory of guided image filtering is adopted since the key parameters of dehazing method using the atmospheric degradation model are difficult to obtain in the conditions of nighttime imaging. In addition, the key model parameters of guided image filter are selected according to the boundary information of original image rather than the original image itself, which makes it more advantageous for dehazing image taken on the hazy night. The experimental results show that the proposed method has better performance than the classical daytime dehazing methods. Additionally, our method exhibits superior effect compared to the well-known nighttime dehazing method in the aspects of suppressing color distortion and background illumination controlling. The evaluations of the experimental results are established on both the subjective and objective aspects, so the conclusion in this paper is more convincing.

Keywords Nighttime image · Image dehazing · Color transfer · Guided image filtering

✉ Xianjia Meng
xianjiam@nwu.edu.cn

[1] School of Information and Technology, Northwest University, Xi'an, Shaanxi 710127, People's Republic of China

[2] Department of Physics, Emory University, Atlanta, GA 30322, USA

[3] School of Electronic and Information Engineering, Xi'an Jiaotong University, Xi'an 710049, People's Republic of China

1 Introduction

With the worsening of air conditions, the occurrence of hazy weather has become dramatically frequent. Hazy weather not only significantly reduces the visibility of human eyes, but also causes the quality degradation of image captured by the camera, leading to the increasing importance of image dehazing. Generally, in the hazy weather, the scattering of haze particles suspending in the air mainly leads to serious quality degradation of captured image, and the scattering effect becomes stronger as the distance from the scene to camera increases. The underlying reasons can be summarized as follows: 1. The light intensity of scene is attenuated in the process of light transmitting from the scene to camera as the distance increases. 2. In the hazy weather, the scattering light of non-scene may enter the camera and participate in imaging [6]. The combination of aforementioned reasons primarily gives rise to the image degeneration in the aspect of contrast and saturation, which is disadvantageous to higher level image analysis and image processing.

Numerous methods have been developed to realize image dehazing motivated by the demand for high-precision images in the last decade. The image dehazing can be basically categorized into two types: The first one is based on the visual enhancement, and the second one concerns the atmospheric degradation model. The underlying mechanism of image degradation is not considered in the first type, which adjusts the contrast and color coefficients of images by correlation algorithms, so that the original image can be recovered visually. This dehazing type is characterized by its low time complexity and wide range of applications. In contrast, the second type is focused on the underlying physical mechanism of imaging deterioration, i.e., the image dehazing is realized by seeking two crucial parameters, atmospheric light value and transmission map, which are used to solve the atmospheric degeneration model.

More specifically for the second dehazing type, the acquisition of atmospheric light value is a prerequisite for solving the atmospheric degeneration model. For the daytime, the atmospheric light that comes from the sunlight passing though the atmosphere is considered as a homogeneous background light. This homogeneous background light is also referred as the global atmosphere light and has a certain value for a specific image. Numerous related methods have been proposed to precisely determine global atmospheric light value for the daytime hazy image with the homogeneous background light [5, 6, 20].

However, the situation becomes more complicated for the nighttime hazy image, in which the background illumination is low and a variety of artificial light sources are presented. It makes the background light highly non-uniform, and numerous successful methods for selecting uniform atmospheric light value cannot be directly employed to determine the non-uniform atmospheric light value in this situation. The purpose of this work is to propose a simple and efficient method for nighttime image dehazing based on the modified models of color transfer and guided image filter to solve the aforementioned problems. The details on the development of proposed method are provided in the following sections.

Inspired by the work of [18], we adopt the color transfer model to the nighttime image dehazing. Differently from the classical model of color transfer with the strategy of overall to overall transfer and then modifies the classical model, the proposed method focuses on the different characteristics of various regions in the original image, which makes it more suitable for solving the problem caused by the low illumination and various artificial light sources.

At the stage of dehazing recovery, the proposed method selects the key parameters in guided filtering image model based on the image boundary information instead of image itself, as a result, the extracted boundary information is neither as much as classical model of guided image filter in [7], nor as little as the model of Kou in [11]. The model of Li is suitable for preserving boundary filtering, but is not beneficial to the enhancement dehazing. The enhancement dehazing based on the modified model of guided image filter has appropriate effect without causing the phenomenon of excessive enhancement, which has been confirmed by corresponding experiments. The performance of our proposed method is shown in Fig. 1. Fig. 1a illustrates the nighttime hazy image, and the reference image and dehazing result are shown in Fig. 1b and c respectively.

The framework of this paper is organized as follows. Section 2 summarizes the existing methods targeting daytime and nighttime dehazing. In Section 3 the proposed method is presented, and the experimental results are shown in Section 4 to demonstrate the effectiveness of our method. The paper is concluded in Section 5.

2 Related work

Considerable progress on daytime image dehazing has been made so far. As mentioned in Section 1, the methods based on the atmospheric degradation model have become the mainstream in image dehazing since they are developed according to the underlying physical mechanism of image degradation. For example, assuming that the reflection intensity of local region in a hazy image is constant, an independent component analysis for estimating the scene reflection intensity is proposed by Fattal in [5]. Furthermore, the assumption of dark channel prior is proposed by He in [6], which is derived from the statistics of large numbers of haze-free images. With the atmospheric degradation model, the atmospheric light value and the optimal estimation of haze-free image can be obtained easily. Following He's seminal work, the corresponding fast method is proposed in [4], and the halo effect is remarkably reduced by template segmentation in the dark channel calculation in [1], and the improved dehazing method on complex imaging background is proposed in [9]. In addition, there have been emerging other representative methods regarding image dehazing in recent years [3, 8, 14, 22].

However, the methods above can hardly be directly applied to nighttime image dehazing owing to the fundamental difference of the atmospheric environment in the nighttime hazy conditions, and the works on dehazing nighttime hazy images are rather limited to the best of

(a) (b) (c)

Fig. 1 Nighttime image dehazing. **a** Nighttime hazy image; **b** Reference image; **c** Dehazing result by proposed method our knowledge. The most representative is the work of [12] by Li and a framework that first weakens the effect of glow in the original nighttime image is proposed, resulting in the original image that consists of direct transmission and airlight only. It can realize the recovery of nighttime hazy image to a certain extent, but they still remain in the background of low illumination. Although this method shows nice effect in the aspect of consistent illumination with the original image after processing, it is adverse to subsequent image recognition and feature extraction in this nighttime environment. Pei in [17] proposes a method for nighttime image dehazing with the classical model of color transfer [18], refine dark channel prior and bilateral filter in local contrast correction. In the nighttime environment, this method improves the scene visibility at the cost of reducing the background consistency.

Inspired by the work of [18], the model of color transfer is applied to our method for nighttime image dehazing. Although it changes the background illumination in the nighttime environment, it is very favorable to the recognition of dark scene, which is the primary purpose of image processing at night. Moreover, differently from the method of [18], a modification is made to the classical model of color transfer in the proposed method, so the key transfer coefficients in the modified model are adjusted dynamically according to the different characteristics of various local regions in the original image, which is designed to replace the classical model of overall to overall transfer characterized by not considering the local diversity of image.

The biggest difference between the aforementioned methods of nighttime image dehazing and ours is reflected at the stage of dehazing recovery. Although both the two methods above are all based on the atmospheric degradation model, they suffer from great difficulties in acquiring the atmospheric light value and the solution of whole degradation model when the nighttime illumination is rather dark and primarily from a variety of artificial light sources, i.e., although the local atmospheric light values can be calculated respectively with regard to different regions, it is difficult to guarantee the accuracy of solution to the atmospheric degradation model and reduce the algorithm complexity.

Considering the particularity of nighttime imaging, we adopt the enhancement dehazing type at the stage of dehazing recovery, and focus on extracting the image boundary information by the theory of guided image filtering which is famous for its excellent performance of boundary preservation, which is proposed by He in [7]. Since then, the guided image filtering has many important applications [10, 19, 21]. It should be pointed out that the boundary information of original image cannot be completely preserved since the solution to guided image filter is an approximate solution in practice, and resultantly the main boundary information rather than the whole one is finally extracted to realize enhancement dehazing. The proposed method can avoid solving the atmospheric degradation model directly in the conditions of nighttime imaging, and make the whole process of nighttime image dehazing simple and effective. Additionally, our method could be used as a preprocessing step for some advanced image/video processing, such as complex event analysis [2] and video semantic recognition [15], which also needs further study.

3 Proposed method

According to the structure characteristics of nighttime image and the color characteristics of reference image with high illumination background, the classical model of color transfer [18] is modified to improve the illumination level of nighttime image, and acquire the transferred image. And then the boundary information of transferred image can then be extracted by the modified model of guided filter. The image boundary layer is amplified by several times and added to the filtered image to realize enhancement dehazing, which can effectively avoid the occurrence of color distortion that always appears in the methods based on the atmospheric degradation model in the nighttime imaging conditions. The schematic sketch of proposed method is shown in Fig. 2. According to the sketch, the two modified models play a significant role in the nighttime image dehazing, which will be discussed in detail in following sections.

3.1 Modified model of color transfer

Color transfer between images is a newly emerging issue in the field of computer vision. The thought of color transfer basically employs two images of source image *Sou* and reference image *Ref* to get a new image which contains the structure characteristics of *Sou* and color characteristics of *Ref* simultaneously. A founded theory as well as the corresponding method for color transfer is proposed by Reinhard in [18], which is based on the coordinate transformation. More specifically, both *Sou* and *Ref* images are transferred from *RGB* color space to $l\alpha\beta$ color space, which can eliminate the strong color correlation of image in *RGB* space. If l represents the achromatic channel and α, β represent the chromatic yellow-blue and red-green opponent channels respectively, the transformation can be expressed as:

$$\begin{cases} l' = \left(\sigma_r^l/\sigma_s^l\right) \times \left(l - M_s^l\right) + M_r^l \\ \alpha' = \left(\sigma_r^\alpha/\sigma_s^\alpha\right) \times \left(\alpha - M_s^\alpha\right) + M_r^\alpha \\ \beta' = \left(\sigma_r^\beta/\sigma_s^\beta\right) \times \left(\beta - M_s^\beta\right) + M_r^\beta \end{cases} \tag{1}$$

where M_s^l, M_s^α, M_s^β represent the mean of *Sou* in l, α, β channels respectively, and M_r^l, M_r^α, M_r^β represent the mean of *Ref* in l, α, β channels respectively. The standard deviation ratios σ_r^l/σ_s^l, $\sigma_r^\alpha/\sigma_s^\alpha$, $\sigma_r^\beta/\sigma_s^\beta$ between *Ref* and *Sou* in l, α, β channels respectively are regarded as the key conversion coefficients in the process of color transfer. Ultimately the newly transferred image which contains the structure characteristics of *Sou* and color characteristics of *Ref* can be appropriately displayed when it is transformed to the *RGB* color space [18, 17].

Although the method of Reinhard has a surprising effect in a variety of applications, it fails to work perfectly when applied to the nighttime image dehazing. According to Eq. (1), the color transfer is based on the conversion coefficients determined by the ratios between the overall standard deviations. Since it does not take full consideration of the different

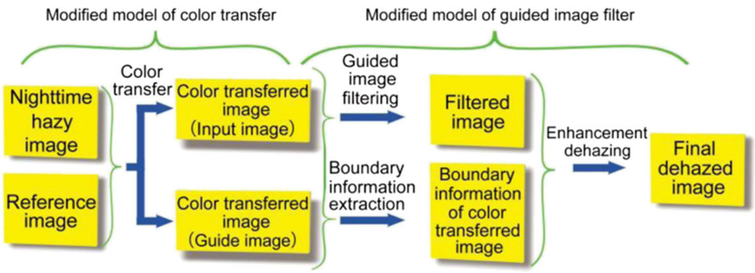


Fig. 2 Schematic sketch of proposed method

characteristics of various regions in *Sou*, it is adverse to preserve and enhance the structure details of dark scene in the conditions of low illumination and various artificial light sources. For this reason, a modified model of color transfer for nighttime image dehazing is proposed, which reads:

$$\begin{cases} l' = \sigma_r^l/\sigma_{s,\Omega(px)}^l \times \left(l - M_s^l\right) + M_r^l \\ \alpha' = \sigma_r^\alpha/\sigma_{s,\ \Omega(px)}^\alpha \times \left(\alpha - M_s^\alpha\right) + M_r^\alpha \ , \forall px \in \Omega(px) \\ \beta' = \sigma_r^\beta/\sigma_{s,\ \Omega(px)}^\beta \times \left(\beta - M_s^\beta\right) + M_r^\beta \end{cases} \tag{2}$$

where $\Omega(px)$ is a local template centered at the pixel px. Compared to Eq. (1), Eq. (2) replaces the overall standard deviations σ_s^l, σ_s^α, σ_s^β by the local standard deviations $\sigma_{s,\Omega(px)}^l$, $\sigma_{s,\ \Omega(px)}^\alpha$, $\sigma_{s,\ \Omega(px)}^\beta$ respectively, which are calculated by the local template $\Omega(px)$ scanning the entire image *Sou*. Consequently, the color transfer can be realized with the local color characteristics of *Sou* by Eq. (2).

In order to verify the effectiveness of modified model, two test images of daytime and nighttime are selected as the source images. As shown in Fig. 3, the color of reference image can be transferred to the color of any source image. Figs. 3a and b show two source images with different structure characteristics respectively, and Figs 3c and d show two reference images with different color characteristics respectively. The transferred results of Figs. 3a and c by the model of Reinhard model and our model are illustrated in Figs. 3e and g respectively, and the transferred results using Fig. 3b and d by the model of Reinhard and our model are shown in Figs. 3g and h respectively. As can be easily seen, since it is focused on the different characteristics of various regions, the modified model makes it more advantageous for details preservation. Meanwhile, it also exhibits the dehazing effect to a certain extent as shown in Fig. 3g. Note that the test images in this paper are taken from the Berkeley Segmentation Dataset and the Internet.

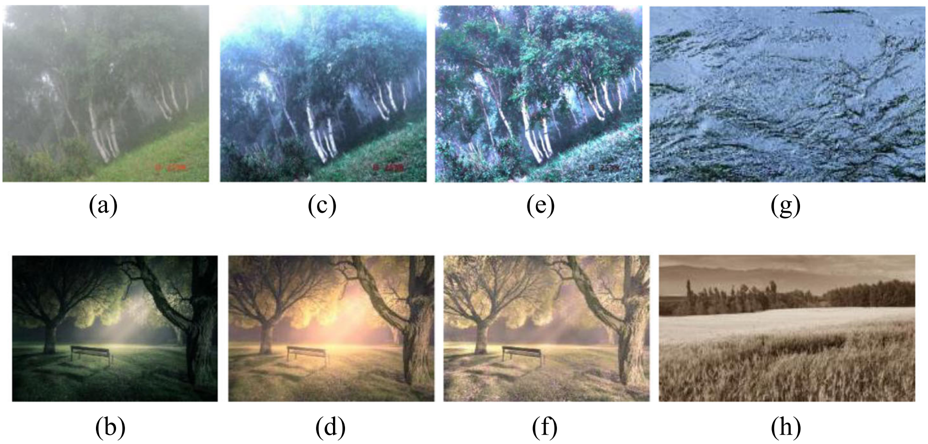


Fig. 3 Image color transfer. **a-b** Two source images; **c-d** Color transfer results of **a** and **b** by Reinhard's model [18] respectively; **e-f** Color transfer results of **a** and **b** by our model respectively; **g-h** Reference images for **a** and **b** respectively

3.2 Modified model of guided image filter

The boundary information of original image can be preserved rather well in the filtered image when the classical guided image filter is applied, which is also proposed by He in [7]. Assuming that the original image is expressed by $X(p)$, and the filtered image expressed by $Z(p)$ is linearly related to the guide image $G(p)$ in a local template $\Omega_{\varsigma_1}\left(p^{'}\right)$ centered at the pixel $p^{'}$. The filtered image $Z(p)$ in this template can be written as:

$$Z(p) = a_{p'}G(p) + b_{p'}, \quad \forall p \in \Omega_{\varsigma_1}\left(p^{'}\right) \tag{3}$$

where $a_{p'}$ and $b_{p'}$ are the constant coefficients in $\Omega_{\varsigma_1}\left(p^{'}\right)$ with the size of $(2\varsigma_1 + 1) \times (2\varsigma_1 + 1)$. Taking the gradient operation for both sides of Eq. (3), we get $\nabla Z(p) = a_{p'}\nabla G(P)$, which means that the filtered image and guide image have the same boundary information in theory.

The linear coefficients $a_{p'}$ and $b_{p'}$ are constant in each local template $\Omega_{\varsigma_1}\left(p^{'}\right)$, and the values of $a_{p'}$ and $b_{p'}$ are obtained by minimizing the energy function:

$$E\left(a_{p'}, b_{p'}\right) = \sum_{p \in \Omega_{\varsigma_1}\left(p'\right)} \left(\left(a_{p'}G(p) + b_{p'} - X(p)\right)^2 + \lambda a_{p'}^2\right) \tag{4}$$

Here, λ is a regularization parameter penalizing the large $a_{p'}$. In practical applications the original image $X(p)$ is usually used as the guide image $G(p)$. Under these circumstances, when the template $\Omega_{\varsigma_1}\left(p^{'}\right)$ moves to the high-variance region, i.e., boundary region, we have $a_{p'} \approx 1$ and $b_{p'} \approx 0$, so the filter approaches the boundary preservation filter here. On the contrary, if the template $\Omega_{\varsigma_1}\left(p^{'}\right)$ moves to the low-variance region, i.e., smooth region, we have $a_{p'} \approx 0$ and $b_{p'} \approx \mu_{\Omega_{\varsigma_1}}\left(P^{'}\right)$, where $\mu_{\Omega_{\varsigma_1}}\left(P^{'}\right)$ is the mean value of template $\Omega_{\varsigma_1}\left(p^{'}\right)$ and the filter approaches the mean filter here. It is worth noting that guided image filter only approaches the boundary preservation filter in the boundary regions since $a_{p'}$ and $b_{p'}$ are obtained by minimizing the energy function Eq. (4). With the linear coefficients $a_{p'}$ and $b_{p'}$, the filtered image $Z(p)$ can be obtained by Eq. (3), and the difference $(X(p) - Z(p))$ is regarded as the boundary image. This boundary image is amplified by several times and added to $Z(p)$, so the enhancement dehazing can be ultimately achieved with this guided image filter [7, 11].

Due to the different characteristics of various regions, the parameter λ is adjusted to adapt the requirement of boundary preservation for each region [13]. Following this, a new energy function is established by Kou in [11], and it is defined as:

$$\begin{cases} E\left(a_{p'}, b_{p'}\right) = \sum_{p \in \Omega_{\varsigma_1}\left(p'\right)} \left(\left(a_{p'}G(p) + b_{p'} - X(p)\right)^2 + \dfrac{\lambda}{\Gamma_G(p')}\left(a_{p'} - \gamma_{p'}\right)^2\right) \\ \Gamma_G\left(p^{'}\right) = \dfrac{1}{N}\sum_{p=1}^{N} \dfrac{\chi\left(p^{'}\right) + \varepsilon}{\chi(p) + \varepsilon} \gamma_{p'} = 1 - \dfrac{1}{1 + e^{\eta\left(\chi(p') - \mu_{\chi,\infty}\right)}} \end{cases} \tag{5}$$

where ε is a small positive constant, and N is the total pixel number of original image. $\chi(p^{'})$ is defined as $\sigma_{G,\varsigma_1}\left(p^{'}\right)\sigma_{G,1}\left(p^{'}\right)$. $\sigma_{G,\varsigma_1}\left(p^{'}\right)$ is a local standard deviation with the template size of $(2\zeta_1 + 1) \times (2\zeta_1 + 1)$, and $\sigma_{G,1}(p^{'})$ is another local standard deviation with the template size of $(2 \times 1 + 1) \times (2 \times 1 + 1) = 3 \times 3$. The parameter ε is a small positive constant and the parameter η is calculated as $4/(\mu_{x,\infty} - \min(\chi(p)))$, in which $\mu_{x,\infty}$ is the mean value of all $\chi(p)$. Compared to Eq. (3), here the value of $a_{p'}$ approaches 1 if the pixel $p^{'}$ is located in the boundary region, and 0 if it is in the smooth region to a higher degree.

As can be seen, Eq. (5) is modified form of the energy function Eq. (4), and the self-adaption parameters are calculated based on the original image in Eq. (5). However, there are likely complex structures and textures in the original image, so the accuracy of the self-adaption parameters calculated by Eq. (5) cannot be guaranteed. For this reason, we calculate the self-adaption parameters according to the boundary image of original image rather than the original image itself in order to improve the accuracy of the self-adaption parameters.

In the background of low illumination and a variety of artificial light sources, if the boundary information is extracted by the classical guided image filter directly, numerous non-major boundaries with high pixel values are also extracted. It is easy to cause local color distortion and excessive enhancement resultantly. The method of [11] has a better performance of boundary preservation because the extracted boundary information is less than the classical guided filter. In other words, the boundary information can be preserved better in the filtered image, but it is not suitable for image dehazing based on the boundary extraction, especially for the nighttime image difficult to extract the image boundaries.

Therefore, Prewitt operator is used in proposed method to calculate the self-adaption parameters in the energy function. Prewitt operator not only has a strong ability to extract the image boundaries that change gradually, but it is also beneficial to suppress image noise. On this basis, we can calculate the significant self-adaption parameters according to the boundary information acquired by Prewitt operator, and a new energy function can be established as:

$$E = \sum_{p \in \Omega_{\varsigma 1}\left(p'\right)} \left[\left(a_{p'} G(p) + b_{p'} - X(p)\right)^2 + \frac{\lambda}{\Gamma_G(\mathrm{B} \circ p')} \left(a_{p'} - \gamma_{\mathrm{B} \circ p'}\right)^2 \right] \tag{6}$$

where $B \circ P^{'}$ is an operation to extract the boundary information in the local template $\Omega_{\varsigma 1}(p^{'})$ centered at the pixel $p^{'}$. In other words, $p^{'}$ of $\Gamma_G\left(p^{'}\right)$ and $\gamma_{P'}$ in Eq. (5) are replaced by $B \circ P^{'}$. The modified model of guided image filter is completely established to this end.

In order to clearly compare the experimental results by the models of He, Kou, and ours, we select the daytime images as the test images here, and the nighttime hazy images are tested in Section 4. Fig. 4a shows the original image, and the boundary extraction results by the models of He, Kou and ours are shown in Figs. 4c, d and e. Note that they are all amplified by 3 times for display. The enhancement dehazing results by the models of He, Kou and ours are shown in Figs. 4f, g and h respectively, and here the enhancement factors are all 5 times. One can see that the model of He extracts too much boundary information as shown in Fig. 4c, as a result, the phenomenon of excessive enhancement appears in Fig. 4f. On the other hand, little boundary information is extracted by the model of Kou as shown in Fig. 4d, so the corresponding result of enhancement dehazing is not obvious in Fig. 4g. By comparison, our model can extract appropriate boundary information to achieve image dehazing with a suitable scale as illustrated in Fig. 4e and h.

To fully demonstrate the modified model of guided image filter, the test image with another scene is selected. Fig. 4b shows the original image, and the boundary images extracted by the models of He, Kou and ours are shown in Figs. 4i, j and k respectively. Note that they are all amplified by 8 times for display. The ultimate enhancement results by the models of He, Kou and ours are shown in Figs. 4l, m and n respectively and here the enhancement factors are all 5 times. It can be seen that these results still support the conclusion above.

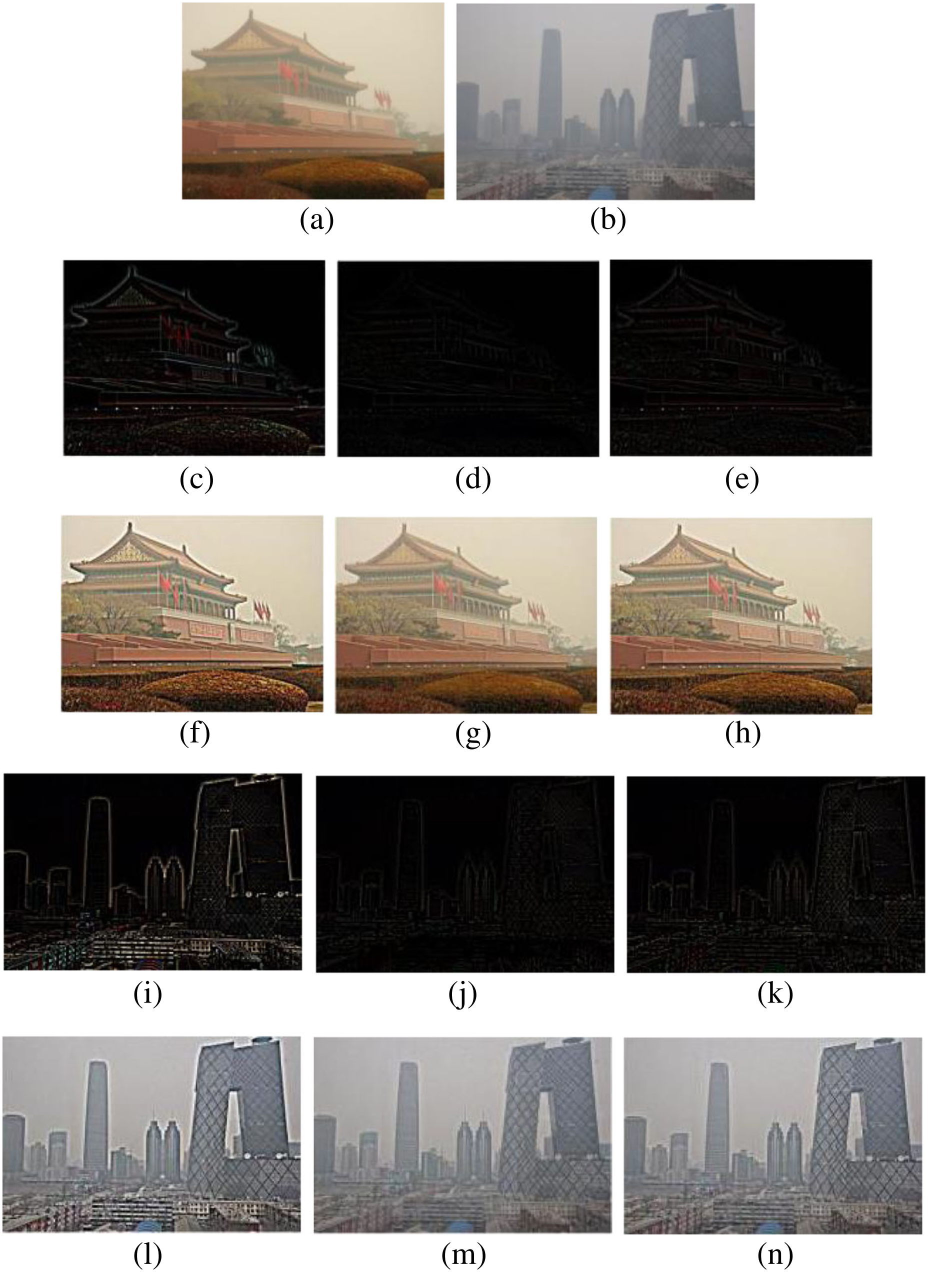
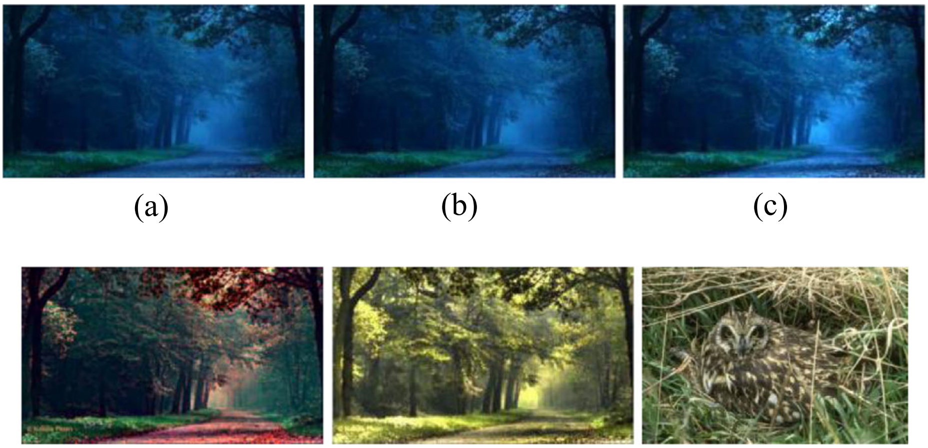


Fig. 4 Enhancement dehazing based on boundary extraction. **a-b** Original hazy images; **c-e** Boundary extraction results of Fig. **a** by He [7], Kou [11], and ours respectively; **f-h** Enhancement dehazing results of Fig. **a** by He [7], Kou [11], and ours respectively; **i-k** Boundary extraction results of Fig. **b** by He [7], Kou [11], and ours respectively; **l-n** Enhancement dehazing results of Fig. **b** by He [7], Kou [11], and ours respectively

4 Experimental results

This section mainly focuses on the comparison between the most representative methods of He [6], Fattal [5], Li [12] and proposed method for the nighttime hazy images. Note that the major coefficients in the methods of Fattal, He and Li are set to the appropriate values in order to sufficiently demonstrate the effectiveness of proposed method. Moreover, in order to further improve its dehazing effect, guided image filtering [7] is applied to the method of He [6] in the process of refining its transmission map, which is different from the proposed method that applies guided image filtering to image dehazing directly. The experiment is performed using the software Matlab2013b, which is installed on a computer with an Intel Core i7-4510 processor.

A nighttime hazy image is selected as the test image as shown in Fig. 5a. Figs. 5b and c show the dehazing results by the methods of He and Fattal respectively. As can be seen, the dehazing effect by the methods of He and Fattal are quite limited since many dark scenes cannot be identified clearly. The dehazing results by the methods of Li and ours are shown in Figs. 5d and e respectively, and Fig. 5f shows the reference image in our method. Because the color of original image is bluish, in order to effectively enhance the visibility of processed image, we choose the reference image with more yellow and green colors. Note that the visual clarity is greatly improved, though the color of processed image is not consistent with original one. The enhancement factor of proposed method is 2 times here. It can be seen that both of them preferably recover the image details in the conditions of low illumination and various artificial light sources, but compared with Fig. 5d, the visual effect of Fig. 5e is obviously much more outstanding due to the flexible control of illumination background in the processed image. It should be pointed out that the dehazing results by the methods of Li and ours do not show the good color uniformity with the original image Fig. 5a, because the identification of low illumination scenes is generally the primary purpose of nighttime image processing.



(a) (b) (c)

(d) (e) (f)

Fig. 5 Experiment I on nighttime image dehazing. **a** Nighttime hazy image; **b** He's result [6]; **c** Fattal's result [5]; **d** Li's result [12]; **e** Our result; **f** Reference image (Because the color of original image is bluish, we choose the reference image with more yellow and green colors)

To further verify the advantages of our method for nighttime image dehazing, another test image is selected, and the results are shown in Fig. 6. Fig. 6a shows the original nighttime hazy image, Figs. 6b and c show the recovery results using the methods of He, Fattal respectively. It is easily seen that these dehazing methods based on the atmospheric degradation model do not exhibit obvious dehazing effect on the nighttime hazy image. The methods of Li and ours are shown in Figs. 6d and e, and two reference images are shown in Figs. 6f and g respectively. The enhancement factor of proposed method is 3 times here, and color transfer is used twice for the nighttime image difficult to process. By comparison, the proposed method for nighttime image dehazing is superior to the method of Li in the aspect of flexible illumination control.

Besides the subjective evaluation above, an objective evaluation is carried out using the no-reference quality evaluator [16] in spatial domain, which can measure the loss degree of image details, and a lower score indicates a better image quality. We chose the dark region of Fig. 5a that is more difficult to restore and the distant region in Fig. 6a to calculate the objective evaluation scores as shown in the red rectangles. The scores by the methods of He, Fattal, Li, and ours are shown in Table 1 respectively. As can be seen from these scores, the proposed method is obviously superior to the other ones. From the objective point of view, it is also proved that our method is effective to nighttime image dehazing.

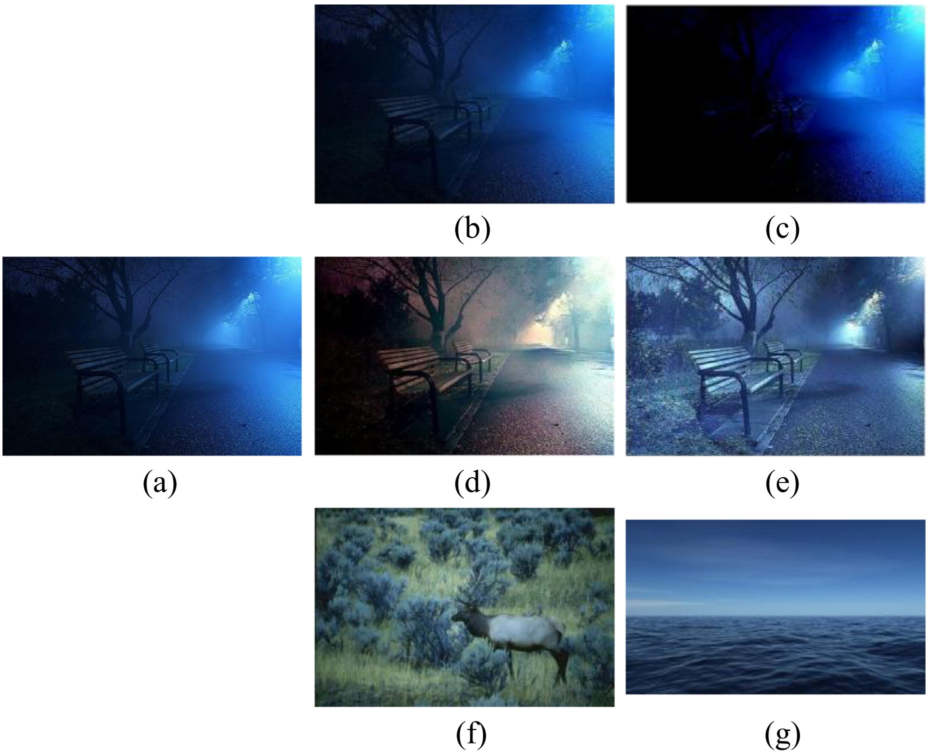


Fig. 6 Experiment II on nighttime image dehazing. **a** Nighttime hazy image; **b** He's result [6]; **c** Fattal's result [5]; **d** Li's result [12]; **e** Our result; **f** Reference image I; **g** Reference image II

Table 1 Objective evaluation scores by no-reference quality evaluator [16]

	Original Images	He's Results	Fattal's Results	Li's Results	Our Results
 Fig. 5(a)	39.7438	39.1318	32.9748	32.6976	**32.1651**
 Fig. 6(a)	25.4725	33.8493	14.3680	42.7215	**11.1179**

5 Conclusion

In conclusion, we propose a simple and efficient method for nighttime image dehazing, which is based on the two modified models of color transfer and guided image filter. At the stage of changing illumination, based on the color transfer theory, the low illumination background of nighttime image is transferred to a higher one flexibly according to the different application purposes. However, due to the interference of various artificial light sources in nighttime image, the classical model of color transfer is replaced by the modified one, in which the characteristics of different regions in the image are considered.

At the stage of image dehazing, we adopt the enhancement dehazing type coupled with a modified model of guided image filter. As a result, the hazy image can be effectively recovered without causing the phenomenon of color distortion and excessive enhancement. Experimental results on a variety of nighttime hazy images demonstrate the effectiveness of proposed method from both the subjective and objective evaluations.

It should be addressed that the proposed method also has two limitations. Although the modified model of color transfer can achieve the better visual effect in the processed image and is more conducive to the subsequent applications, it has a poor performance in the aspect of color uniformity. The inconsistency can be eliminated by appropriately selecting the reference image, but it cannot be eliminated completely. Meanwhile, owing to the lack of obvious boundary structures for the distant scenes, our method may fail to recover these scenes there, and we leave these problems above for future research.

Acknowledgements This work was supported by National Natural Science Foundation of China (No. 41601353, 61503300 and 61502387), and Foundation of Key Laboratory of Space Active Opto-Electronics Technology of Chinese Academy of Sciences (No. AOE-2016-A02), and Scientific Research Program Funded by Shaanxi Provincial Education Department (No. 16JK1765), and Foundation of State Key Laboratory of Transient Optics and Photonics, Chinese Academy of Sciences (No. SKLST201614), and Natural Science Basic Research Plan in Shaanxi Province of China (No. 2017JQ4003).

References

1. Bui TM, Tran HN, Kim W, Kim S (2014) Segmenting dark channel prior in single image dehazing. Electron Lett 50(7):516–518
2. Chang X, Yu YL, Yang Y, Xing EP (2016) Semantic Pooling for Complex Event Analysis in Untrimmed Videos. IEEE Trans Pattern Anal Mach Intell. doi:10.1109/TPAMI.2016.2608901
3. Chen B-H, Huang S-C, Ye JH (2015) Hazy image restoration by bi-histogram modification. ACM Trans Intell Syst Technol 6(4):1–17
4. Cheng FC, Lin CH, Lin JL (2012) Constant time O(1) image fog removal using lowest level channel. Electron Lett 48(22):1404–1406
5. Fattal R (2008) Single image dehazing. ACM Trans Graph 27(3):1–9
6. He K, Sun J, Tang X (2010) Single image haze removal using dark channel prior. IEEE Trans Pattern Anal Mach Intell 33(12):2341–2353
7. He K, Sun J, Tang X (2013) Guided image filtering. IEEE Trans Pattern Anal Mach Intell 35(6): 1397–1409
8. Huang S-C, Ye J-H, Chen B-H (2015) An advanced single image visibility restoration algorithm for real-world hazy scenes. IEEE Trans Ind Electron 62(5):2962–2972
9. Jiang B, Zhang W, Meng H, Ru Y, Zhang Y, Ma X (2015) Single image haze removal on complex imaging background. IEEE International Conference on Software Engineering and Service Sciences 280–283
10. Jiang B, Zhang W, Zhao J, Ru Y, Liu M, Ma X, Chen X, Meng H (2016) Gray-scale image dehazing guided by scene depth information. Math Probl Eng 2016:1–10
11. Kou F, Chen W, Wen C, Li Z (2015) Gradient domain guided image filtering. IEEE Trans Image Process 24(11):4528–4539
12. Li Y, Tan RT, Brown MS (2015) Nighttime haze removal with glow and multiple light colors. IEEE Int Conf Comput Vis 226-234
13. Li Z, Zheng J, Zhu Z, Yao W, Wu S (2015) Weighted guided image filtering. IEEE Trans Image Process 24(1):120–129
14. Lu H, Li Y, Nakashima S, Serikawa S (2016) Single image dehazing through improved atmospheric light estimation. Multimed Tool Appl 75(24):17081–17096
15. Luo M, Chang X, Nie L, Yang Y, Hauptmann A, Zheng Q (2017) An Adaptive Semisupervised Feature Analysis for Video Semantic Recognition. IEEE Trans Cybern. doi:10.1109/TCYB.2017.2647904
16. Mittal A, Moorthy AK, Bovik AC (2012) No-reference image quality assessment in the spatial domain. IEEE Trans Image Process 21(12):4695–4708
17. Pei SC, Lee TY (2012) Nighttime haze removal using color transfer pre-processing and dark channel prior. IEEE Int Conf Image Proc:957–960
18. Reinhard E, Ashikhmin M, Gooch B, Shirley P (2001) Color transfer between images. IEEE Comput Graph Appl 21(5):34–41
19. Shi Z, Xu B, Zheng X, Zhao M (2016) An integrated method for ancient Chinese tablet images de-noising based on assemble of multiple image smoothing filters. Multimed Tool Appl 75(19): 12245–12261
20. Tarel JP, Hautière N (2009) Fast visibility restoration from a single color or gray level image. IEEE Int Conf Comput Vis 30(2):2201–2208
21. Zheng X, Miao Q, Shi Z, Fan Y, Shui W (2016) A new artistic information extraction method with multi channels and guided filters for calligraphy works. Multimed Tool Appl 75(14):8719–8744
22. Zhu Q, Mai J, Shao L (2015) A Fast Single Image Haze Removal Algorithm Using Color Attenuation Prior. IEEE Trans Image Process 24(11):3522–3533