NIGHTTIME SINGLE IMAGE HAZE REMOVAL EMPLOYING MULTI-SCALE GAUSSIAN FILTER

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***Abstract*—Recently, many studies on haze removal have been conducted. For a daytime hazy image, there are many effective dehazing algorithms. However, these methods can't effectively remove haze for a nighttime hazy image. In nighttime conditions, there may be multiple light sources such as street lamps and neon signs. In such conditions, the atmospheric light tends to be non-uniform in the entire scene. Due to the non-uniform atmospheric light, nighttime haze removal is a very challenging problem. In this paper, we propose a nighttime haze removal method based on the Retinex theory. In the proposed method, the atmospheric light estimation is achieved based on the assumption that the atmospheric light varies smoothly in space by the analogy of the Retinex theory. Concretely, the atmospheric light is estimated as the maximum value of outputs of multi-scale Gaussian filters. Through experiments with some images, we verify the effectiveness of the proposed method.**

I. INTRODUCTION

When images or videos are captured in outdoors, haze(e.g., fog and mist) may appear in the images or videos depending on the weather. The presence of haze significantly degrades the visibility of the images or videos. Such degradation of visibility can cause severe problems for outdoor surveillance camera systems and in-vehicle camera systems. To solve this problem, many studies on haze removal have been conducted [1]–[6].

He et al. proposed a dehazing method based on the dark channel prior [4]. This method can efficiently improve the visibility of a hazy image by removing haze though it is very simple and fast. However, this method can't effectively remove haze for a nighttime hazy image. Recently, some methods for nighttime haze removal have been proposed [5], [6]. In these methods, the atmospheric light is locally estimated based on the assumption that the atmospheric light in nighttime scene is non-uniform. Compared to He et al.'s method, these methods can remove haze from a nighttime hazy image and significantly improve the contrast of the image. However, these methods tend to cause over-enhancement in regions around light sources, or tend to amplify the noise and generate roughness in flat areas.

In this paper, we propose a nighttime haze removal method based on the Retinex theory [7]. The atmospheric light estimation in the proposed method is based on the assumption that the atmospheric light varies smoothly in space. When a Gaussian filer with a large standard deviation is used in the atmospheric light estimation process, the contrast of an input hazy image is significantly improved. However, setting the standard deviation to a large value can also cause over-enhancement in bright regions such as the regions around light sources. To cope with this problem, in the proposed method, filtering results of Gaussian filters with small, medium and large standard deviations are combined by using the max function. By doing so, the proposed method can enhance the contrast of a nighttime hazy image suppressing over-enhancement in the bright regions. In addition, the algorithm of the proposed method is very simple and its computational cost is low. Through experiments with some images, we verify the effectiveness of the proposed method.

II. DEHAZING METHOD BASED ON THE DARK CHANNEL PRIOR

Except for the process of the atmospheric light estimation, the algorithm of the proposed dehazing method in this paper is the same as the dehazing method proposed by He et al. In this section, He et al.'s dehazing method is explained.

The observation model for a hazy image [8] is given as follows:

$$\boldsymbol{I}^c(x,y) = \boldsymbol{J}^c(x,y)t(x,y) + \boldsymbol{A}^c(x,y)(1-t(x,y)). \quad (1)$$

where $x \in \{1,2,\cdots,P\}$, $y \in \{1,2,\cdots,Q\}$, $c \in \{R,G,B\}$. $\boldsymbol{I}^c(x,y)$ is the pixel value in channel c at the location (x,y) of an observed hazy image. $\boldsymbol{J}^c(x,y)$ is the pixel value in channel c at the location (x,y) of a haze-free image (i.e. direct light from the objects). $\boldsymbol{A}^c(x,y)$ is the intensity in channel c of the atmospheric light at the location (x,y). $t(x,y)$ is the transmittance at the location (x,y). If $\boldsymbol{A}(x,y)$ and $t(x,y)$ are obtained, $\boldsymbol{J}^c(x,y)$ can be estimated by the following equation which is a transformed expression of Eq.(1):

$$\boldsymbol{J}^c = \frac{\boldsymbol{I}^c(x,y) - \boldsymbol{A}^c(x,y)}{\max(t(x,y),t_0)} + \boldsymbol{A}^c(x,y). \quad (2)$$

where t_0 should be set to be a small positive value for preventing dividing by 0. In He et al.'s method, the atmospheric light and the transmittance are estimated based on the dark channel prior. The dark channel prior is the priori knowledge that when a small region is extracted in a haze-free image, there likely to be a pixel with a very small pixel value in one of the RGB components. In He et al.'s method, firstly dark channel image $\boldsymbol{I}^{\text{dark}}$ is obtained as follows:

$$I^{\text{dark}}(x,y) = \min_{(i,j)\in\Omega(x,y)} \left(\min_{c\in\{R,G,B\}} \left(I^c(i,j)\right) \right). \tag{3}$$

where $I^{\text{dark}}(x,y)$ is the pixel value at the location (x,y) of $\boldsymbol{I}^{\text{dark}}$. $\Omega(x,y)$ is the region around the location (x,y) whose size is $r_\Omega \times r_\Omega$ pixels. After obtaining $\boldsymbol{I}^{\text{dark}}$, the top 0.1% brightest pixls of $\boldsymbol{I}^{\text{dark}}$ are extracted. From the pixels, the pixel with the highest luminance in $\boldsymbol{I}$ is selected and the color of the pixel is used as the color of the atmospheric light. Though there are various definitions of luminance, luminance is defined as the average value of RGB components in this paper. After calculating atmospheric light, $\tilde{t}(x,y)$ is estimated by the following Eq.(4):

$$\tilde{t}(x,y) = 1 - \omega \min_{(i,j)\in\Omega(x,y)} \left(\min_{c\in\{R,G,B\}} \left(\frac{I^c(i,j)}{A^c(i,j)} \right) \right). \tag{4}$$

where ω is a parameter to adjust the degree of haze removal. The image whose pixel value at the location (x,y) is $\tilde{t}(x,y)$ is denoted $\tilde{t}$. When the output image is obtained by using $\tilde{t}$ as the transmittance map, block-like artifacts are generated. In Ref. [9], He et al. showed that a guided filter is effective for removing such artifacts. The image obtained by applying a guided filter to $\tilde{t}$ with the luminance image of $\boldsymbol{I}$ as a guide image is denoted as t. Using the refined transmittance map t, the final output image is obtained with Eq.(2).

III. PROPOSED METHOD

In the proposed method, the atmospheric light is locally estimated based on the assumption that the atmospheric light is not uniform in the entire image. The proposed method is based on the Retinex theory [7]. In the theory, each pixel value of an observed image is decomposed into the illumination component and the reflectance component. The illumination component represents global brightness and the reflectance component represents spectral reflection characteristics of the objects. Since the illumination varies smoothly in space, many studies based on the Retinex theory such as Ref. [10] estimate the illumination component by applying a Gaussian filter to the observed image. Based on the assumption that the atmospheric light varies smoothly in space as well as the illumination, the atmospheric light is estimated by applying a Gaussian filter to the input image in the proposed method. After calculating the atmospheric light, the output image is obtained in the same way as described in section 2.

In the proposed method, a Gaussian filter is applied to the input image, and its output at the location (x,y) is expressed as follows:

$$\boldsymbol{G}^c(x,y) = \frac{\sum_{(i,j)\in\Phi(x,y)} e^{-\frac{1}{2\sigma^2}((i-x)^2+(j-y)^2)} \cdot \boldsymbol{I}^c(i,j)}{\sum_{(i,j)\in\Phi(x,y)} e^{-\frac{1}{2\sigma^2}((i-x)^2+(j-y)^2)}}, \tag{5}$$

where $\Phi(x,y)$ is the region around the location (x,y) whose size is $(2r_\Phi+1)\times(2r_\Phi+1)$ pixels. In the proposed method, r_Φ is determined by $r_\Phi = \lceil 3\sigma \rceil$ according to σ. $\lceil\cdot\rceil$ is a ceiling function.

Then, the atmospheric light at the location (x,y) is calculated as follows:

$$\boldsymbol{A}^c_{\text{prop}}(x,y) = \max\{\boldsymbol{G}^c_{\text{S}}(x,y), \boldsymbol{G}^c_{\text{M}}(x,y), \boldsymbol{G}^c_{\text{L}}(x,y)\}. \tag{6}$$

where $\boldsymbol{G}^c_{\text{S}}(x,y)$, $\boldsymbol{G}^c_{\text{M}}(x,y)$, $\boldsymbol{G}^c_{\text{L}}(x,y)$ are $\boldsymbol{G}^c(x,y)$ in Eq.(5) when σ are σ_{S}, σ_{M} and σ_{L}, respectively. σ_{S}, σ_{M} and σ_{L} are set as small, medium and large value, respectively.

$\boldsymbol{G}^c_{\text{S}}(x,y)$ takes a large value in the bright regions such as the regions around light sources because $\boldsymbol{G}^c_{\text{S}}(x,y) \simeq \boldsymbol{I}^c(x,y)$ holds and $\boldsymbol{I}^c(x,y)$ is large. On the other hand, in such regions, $\boldsymbol{G}^c_{\text{L}}(x,y)$ tends to take a smaller value than $\boldsymbol{G}^c_{\text{S}}(x,y)$ due to the influence of the pixels in distant dark areas. Hence, $\boldsymbol{A}^c_{\text{prop}}(x,y) = \boldsymbol{G}^c_{\text{S}}(x,y)$ tends to hold and over-enhancement is suppressed in the regions. In the regions which are distant from light sources and dark, $\boldsymbol{G}^c_{\text{S}}(x,y)$ tends to take a small value. On the other hand, $\boldsymbol{G}^c_{\text{M}}(x,y)$ and $\boldsymbol{G}^c_{\text{L}}(x,y)$ are likely to be affected by the intensities of bright pixels such as the pixels around light sources. Hence, $\boldsymbol{G}^c_{\text{M}}(x,y)$ and $\boldsymbol{G}^c_{\text{L}}(x,y)$ tend to take larger value than $\boldsymbol{G}^c_{\text{S}}(x,y)$ and $\boldsymbol{A}^c_{\text{prop}}(x,y) = \boldsymbol{G}^c_{\text{M}}(x,y)$ or $\boldsymbol{A}^c_{\text{prop}}(x,y) = \boldsymbol{G}^c_{\text{L}}(x,y)$ tends to hold. As a result, haze is removed sufficiently and the contrast is improved in the regions which is distant from light sources and dark.

IV. EXPERIMENTS

In order to verify the effectiveness of the proposed method, the proposed method was compared with Ancuti et al.'s method [5] and Yu et al.'s method [6].

The parameters in Ancuti et al.'s method and Yu et al.'s method were set according to Refs. [5], [6], respectively. In the proposed method, ϵ and r for the guided filter [9] were set as 0.001 and 20, respectively. σ_{Small}, σ_{Middle} and σ_{Large} were set as $\lceil 0.001\alpha \rceil$, $\lceil 0.01\alpha \rceil$ and $\lceil 0.1\alpha \rceil$, respectively. r_Ω and t_0 was set as 15 and 0.1, respectively.

Figs. 1, 2 and 3 show the results of the proposed method and the comparison methods.

Fig. 1 shows the results for the image #1. As you can see from Fig. 1(b), severe over-enhancement occurred in the regions around light sources in Ancuti et al.'s method. Yu et al.'s method successfully improves the contrast of the image overall. However, haze remains in the region around the foot of a building in the left side of the resultant image as shown in Fig. 1(c). On the other hand, the proposed method effectively removes haze while suppressing over-enhancement as shown in Fig. 1(d).

Fig. 2 shows the results for the image #2. As you can see from Fig. 2(b), many details such as lines carved upon containers are lost due to over-enhancement in Ancuti et al.'s method. Yu et al.'s method effectively removes haze and the visibility of the resultant image is higher than the original image. However, roughness degrades the quality of the resultant image in the sky region. In addition, lines carved upon containers are hardly recognizable due to over-enhancement as shown in Fig. 2(c). On the other hand, roughness in the sky region and over-enhancement in the regions around light

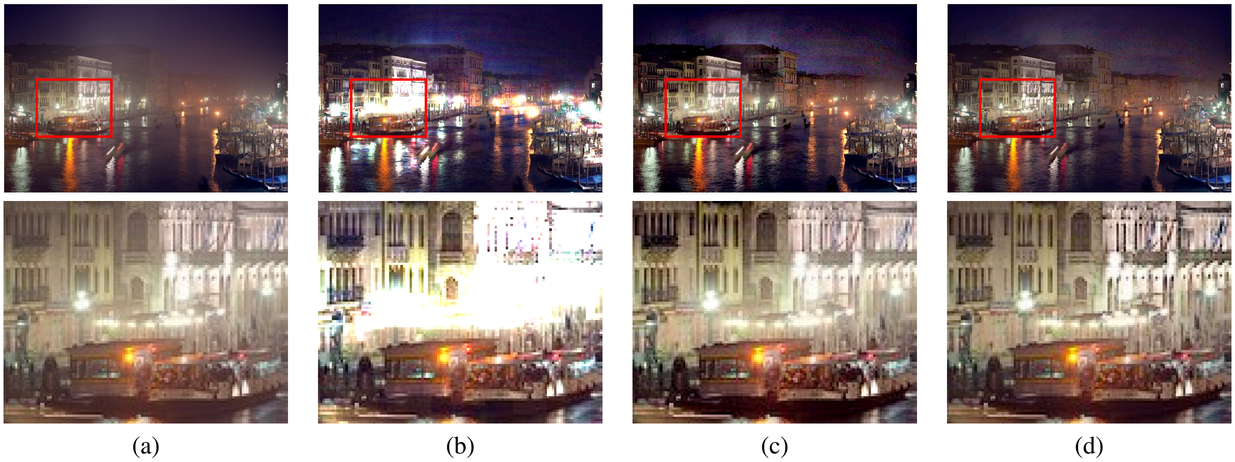
(a) (b) (c) (d)

Fig. 1. The results for image #1. (a) Original image, (b) Ancuti et al's method, (c) Yu et al.'s method, (d) The proposed method. The bottom row shows a larger version of the excerpt from the top row.

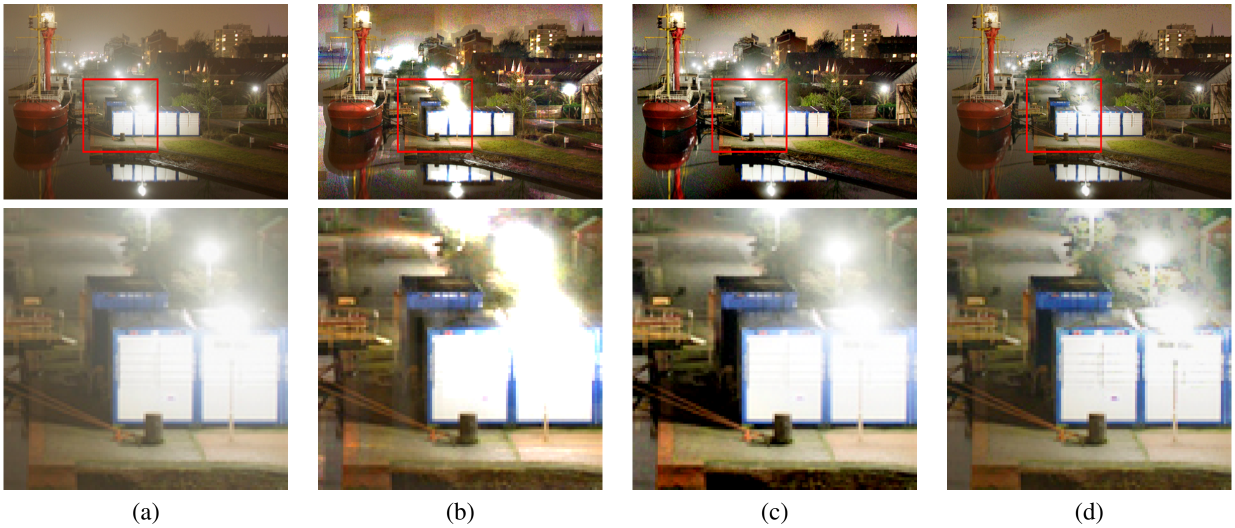
(a) (b) (c) (d)

Fig. 2. The results for image #2. (a) Original image, (b) Ancuti et al's method, (c) Yu et al.'s method, (d) The proposed method. The bottom row shows a larger version of the excerpt from the top row.

sources are not observed in the proposed method as shown in Fig.2(d). In addition, the proposed method removes haze sufficiently and the details such as lines carved upon containers can be seen more clearly than those in the original image.

Fig. 3 shows the results for the image #3. As you can see from Fig. 3(b), many regions in the resultant image of Ancuti et al.'s method are suffered from over-enhancement. Though Yu et al.'s method improves the contrast of the image overall, haze remains in some regions such as the region around a sign in the left side of the resultant image as shown in Fig. 3(c). On the other hand, the proposed method successfully removes haze and the contrast of the region around the sign is high as shown in Fig.3(d).

For quantitative evaluation, MLSDD (Mean of Local Standard Deviation of luminance in Detailed area) and MLSDF (Mean of Local Standard Deviation of luminance in Flat area) were used. In order to calculate MLSDD and MLSDF, firstly the original image is divided into non-overlap blocks which contain 50×50 pixels. Then, local standard deviation of luminance are calculated for each block. After that, the blocks whose standard deviation of luminance are in top 10% are extracted. The extracted blocks are denoted as detailed area in this paper. The blocks whose standard deviation of luminance are in bottom 10% are also extracted. The extracted blocks are denoted as flat area in this paper. MLSDD and MLSDF are calculated as the mean values of the local standard deviation of the blocks in detailed area and flat area, respectively. Note that the determination of whether a block belongs to flat area or detailed area is made in the original image. High score of MLSDD indicates that the local contrast in detailed area is high. On the other hand, low score of MLSDF indicates that flat area in the original image remains flat in the resultant image. It also indicates that noise amplification and occurring of roughness is suppressed in flat area.

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

Fig. 3. The results for image #3. (a) Original image, (b) Ancuti et al's method, (c) Yu et al.'s method, (d) The proposed method. The proposed method. The bottom row shows a larger version of the excerpt from the top row.

TABLE I

MLSDD AND MLSDF. "DETAIL" AND "FLAT" STAND FOR MLSDD AND MLSDF, RESPECTIVELY. "ANCUTI," "YU" AND "PROP." MEANS ANCUTI ET AL.'S, YU ET AL.'S AND THE PROPOSED METHODS, RESPECTIVELY.

Image	Image #1		Image #2		Image #3	
	detail	flat	detail	flat	detail	flat
Original	36.8	5.4	54.4	6.0	50.8	3.3
Ancuti	52.4	13.6	78.1	22.1	75.1	28.4
Yu	40.7	8.9	85.5	30.0	70.1	18.1
Prop.	36.8	5.4	68.3	15.7	56.0	9.3

Table I shows MLSDD and MLSDF. As you can see from Table I, Ancuti et al.'s method generates the highest score in MLSDD for most of the tested images. However, Ancuti et al.'s method tends to cause over-enhancement in regions around light sources as shown in qualitative evaluation. On the other hand, there is no significant difference between Yu et al.'s method and the proposed method in regard to MLSDD for most of the tested images. This indicates that the proposed method enhanced the contrast of tested images in detailed area as much as Yu et al.'s method. Furthermore, MLSDF is greatly increased from the original image for both Ancuti et al.'s and Yu et al.'s methods. Though MLSDF is also increased in the proposed method, the increase is smaller than those of Ancutiet al's and Yu et al.'s methods. The reason for the large increase of MLSDF in Ancuti et al.' and Yu et al.' methods is that the over-enhancement such as noise amplification occurred in flat area.

V. Conculusions

In this paper, we proposed a nighttime haze removal method based on the Retinex theory. In the proposed method, filtering results of Gaussian filters with small, medium and large standard deviations are combined by using the max function, and then used as the estimated atmospheric light. Experimental results illustrated that the proposed method can effectively remove haze while suppressing over-enhancement.

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