SINGLE IMAGE HAZE REMOVAL WITH WLS-BASED EDGE-PRESERVING SMOOTHING FILTER

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ABSTRACT

Images captured under hazy conditions have low contrast and poor color. This is primarily due to air-light which degrades image quality according to the transmission map. The approach to enhance these hazy images we introduce here is based on the 'Dark-Channel Prior' method with image refinement by the 'Weighted Least Square' based edge-preserving smoothing. Local contrast is further enhanced by multi-scale tone manipulation. The proposed method improves the contrast, color and detail for the entire image domain effectively. In the experiment, we compare the proposed method with conventional methods to validate performance.

***Index Terms*—** Air-light, dehazing, image smoothing, multi-scale tone manipulation, transmission map

1. INTRODUCTION

Generally, images in hazy condition exhibit poor contrast and corrupted color. One of the causes is that the light is attenuated as it travels through the haze, resulting less image radiance reaching the imaging sensor. The light scattered by haze particles, as it travels through the air, is called "air-light" [1]-[4]. Air-light creates a significant degradation of image quality according to the transmission map.

There have been a number of studies aimed at the restoration of single hazy image. Oakley et al. restored hazy image using a cost function formulated by normalized standard deviation of the entire image [5]. Since they assumed every pixel has the same depth, it is not appropriate to a hazy image that consists of different depth associated with each pixel. Fattal et al. proposed a single image dehazing method using albedo of the scene [6]. They estimated the transmitted object radiance using statistical independence between shading and albedo. However, this method requires sufficient color information and its performance greatly depends on the statistical information of the hazy image. Tan et al. proposed a hazy image enhancement method using color constancy [7]. They used a color invariant property under hazy conditions. However, this method could not successfully eliminate the actual air-light because transmission map was not employed. K. He et al. restored a hazy image using the Dark Channel Prior (DCP) for estimating the transmission map [8]. However, since image matting for refining of transmission has high computational complexity, this method requires a large processing time. K. Gibson et al. proposed a Median Dark Channel Prior (MDCP) to accelerate processing without refinement [9]. Although MDCP significantly reduces the processing time compared to He's work [8], artificial halo artifacts still remain in the transmission map. J. Yu et al. proposed a fast single image fog removal algorithm using edge-preserving smoothing [10]. They estimated the transmission map refined by the Weighted Least Square (WLS) based smoothing [17] after acquiring a rough estimation of the atmospheric veil from pixel-based DCP. However, it may not render images of near bright objects well.

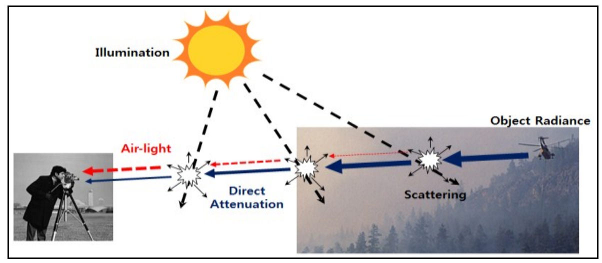

Fig. 1. Effects of atmospheric scattering.

Unlike the pixel-based DCP, we present in this paper a DCP based approach of estimating the transmission map using finite sized patches for accurate rendering of near bright objects. Local contrast was enhanced by using a multi-scale tone manipulation.

This paper is organized as follows. In Section 2, the haze image modeling is presented. Section 3 describes how the scene radiance is restored. Section 4 describes the local contrast enhancement while Section 5 presents the experimental results. Finally, we conclude the paper in Section 6.

2. HAZY IMAGE MODELING

In general, the exact nature of scattering is highly complex and depends on the types, size, orientation and distributions of particles constituting the media as well as wavelengths, polarization states and direction of the incident light [11].

Narasimhan et al. summarized the aforementioned degradation process of 'Attenuation' and 'Air-light' [12]-[15]. The first factor is the direct attenuation of light from a scene point to the observer as a function of the distance it traveled. The second factor is scattered ambient light in the atmosphere reaching to the observer in addition to the radiance propagated from the scene. Based on these two sources, the total irradiance received by the sensor is

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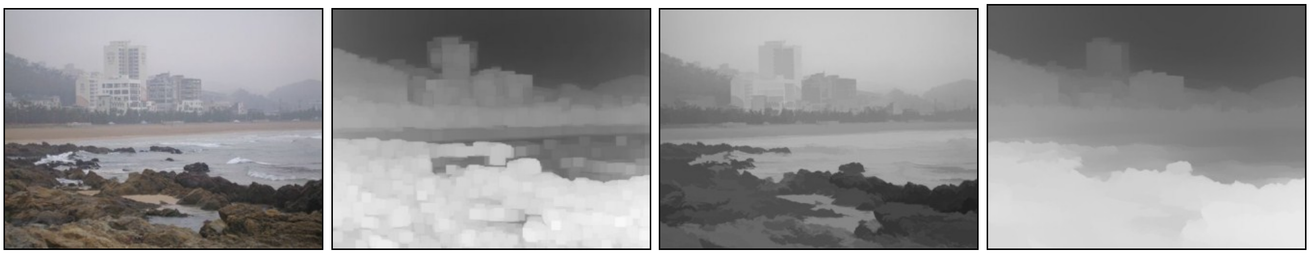


(a) (b) (c) (d)

Fig. 2. Refining procedure from the rough transmission. (a) Input hazy image. (b) Rough transmission map. (c) Processed image by morphological grayscale reconstruction. (d) Refined transmission map using WLS-based smoothing filter from (b), (c).

usually described by the sum of the direct attenuated irradiance and the air-light irradiance as depicted in Fig. 1.

The atmospheric scattering model which is widely used in hazy images is defined as follows [8, 9],

$$\mathbf{I}(p) = \mathbf{J}(p)r(p) + \mathbf{A}(1 - r(p)), \tag{1}$$

where, p is a spatial location in the image, **I** is the observed intensity, **J** is the scene radiance, **A** is the atmospheric light which is assumed to be globally constant. r is the medium transmission describing the portion of the light that is not scattered and reaches the camera. $\mathbf{J}(p)r(p)$ is the direct attenuation term and $\mathbf{A}(1 - r(p))$ is the air-light term [6, 8]. As the transmission, r, decreases, the air-light accumulates and becomes more intense in the hazy images. Essentially, the goal of single image dehazing is to recover **J** from (1).

3. SCENE RADIANCE RESTORATION

3.1. Estimating the rough transmission

It's necessary to determine the parameters, r, to restore hazy images as defined in (1). We estimate rough transmission map using DCP which was proposed in the work of K. He et al. [8]. DCP is a characteristic of outdoor haze-free images which at least one color channel has some pixels whose intensity are very low and close to zero. For an arbitrary image **J**, its dark channel J^{dark} is defined by

$$J^{dark}(p) = \min_{q\in\Omega(p)}\left(\min_{c\in\{r,g,b\}} J^c(q)\right), \tag{2}$$

where, p is a spatial location in the image, $\Omega(p)$ is a local patch centered at p. J^c is a color channel of **J**.

DCP model essentially postulates that if **J** is an outdoor haze-free image, J^{dark} is low and tends to be zero [8]:

$$J^{dark} \to 0 \tag{3}$$

K. He et al. generalized this concept and proposed a novel prior for image dehazing. From DCP, the rough transmission is estimated by [8]

$$\tilde{r}(p) = 1 - \mu \min_{q\in\Omega(p)}\left(\min_{c\in\{r,g,b\}} \frac{\mathbf{I}^c(q)}{\mathbf{A}^c}\right), \tag{4}$$

where, μ is a constant fixed at 0.95, while $\mathbf{I}^c$ and $\mathbf{A}^c$ are color channels of **I**, **A**.

3.2. Refinement with edge-preserving smoothing filter

Since the rough transmission is estimated by a local patch, DCP may result some halos and block artifacts. Therefore, further refinement of the rough transmission map is necessary. K. He et al. refined the rough transmission map using soft matting [16]. However, it results a high computational complexity and processing time. To remedy this, we propose refinement of the rough transmission map using a WLS -based smoothing filter [17]. With this approach a significant reduction in processing time and eliminations of the block artifacts can be achieved.

The WLS-based edge-preserving smoothing filter minimizes following object function [17].

$$\sum_p\left((r_p - \tilde{r}_p)^2 + \lambda\left(w_{x,p}(h)\left(\frac{\partial r}{\partial x}\right)_p^2 + w_{y,p}(h)\left(\frac{\partial r}{\partial y}\right)_p^2\right)\right), \tag{5}$$

where the subscript p denotes the spatial location of a pixel. $\tilde{r}$ is rough transmission as an input image. r is refined transmission as an output image. λ is a constant value to control the smoothing rate. That is, increasing the value λ results in progressively smoother images r. $w_{x,p}(h)$ and $w_{y,p}(h)$ are the smoothness weights defined by

$$w_{x,p}(h) = \left(\left|\frac{\partial h}{\partial x}\right|_p^\alpha + \varepsilon\right)^{-1},\ w_{y,p}(h) = \left(\left|\frac{\partial h}{\partial y}\right|_p^\alpha + \varepsilon\right)^{-1}, \tag{6}$$

where, h is an image processed by morphological grayscale reconstruction [18] from a hazy image. Although these weights serve the purpose of smoothing the rough transmission map to minimize the effect of local textures, these weights are reduced to small values when there is a large image contrast or local gradient due to differences in distances. Exponent α determines the sensitivity to the gradients of h and ε is a small constant to prevent division by zero in (6). We fix it to 10^{-4} for all experiment results.

Refined transmission can be expressed using the formula in (5), given by

(a) (b) (c)

Fig. 3. Recovered images using proposed method (a) Input hazy image. (b) Recovered scene radiance (c) Image processed by local contrast enhancement

$$r = \left(\mathbf{I} + \lambda(\mathbf{D}_x^T \mathbf{A}_x \mathbf{D} + \mathbf{D}_y^T \mathbf{A}_y \mathbf{D}_y)\right)^{-1} \tilde{r}, \tag{7}$$

where, $\mathbf{A}_x$ and $\mathbf{A}_y$ are diagonal matrices containing the smoothness weights $w_x(h)$ and $w_y(h)$, respectively, and $\mathbf{D}_x$, $\mathbf{D}_y$ are discrete differentiation operators. Due to the smoothness weights, the rough transmission can be refined similarly to the hazy image depicted as Fig. 2.

3.3. Estimating the Atmospheric Light

To recovering the scene radiance, we should estimate the atmospheric light. The atmospheric light is the light in the most haze-opaque region.

In Tan's work [7], they used the brightest pixels in the hazy image as the atmospheric light. However, when the white object is in the image, this method is not appropriate. Therefore, we use the atmospheric light proposed by He's work [8]. They used the pixels with highest intensity in the hazy image, after the top 0.1% brightest pixels were picked in the dark channel.

3.4. Recovering the Scene Radiance

From the transmission map and the atmospheric light, we can recover the scene radiance according to (1) given by

$$\mathbf{J}(p) = \frac{\mathbf{I}(p) - \mathbf{A}}{\max(r(p), r_0)} + \mathbf{A} \tag{8}$$

where r_0 is a user-specified constant. In the experiments, we fix this value to 0.1. Fig 3(b) shows recovered scene radiance from (8).

4. LOCAL CONTRAST ENHANCEMENT

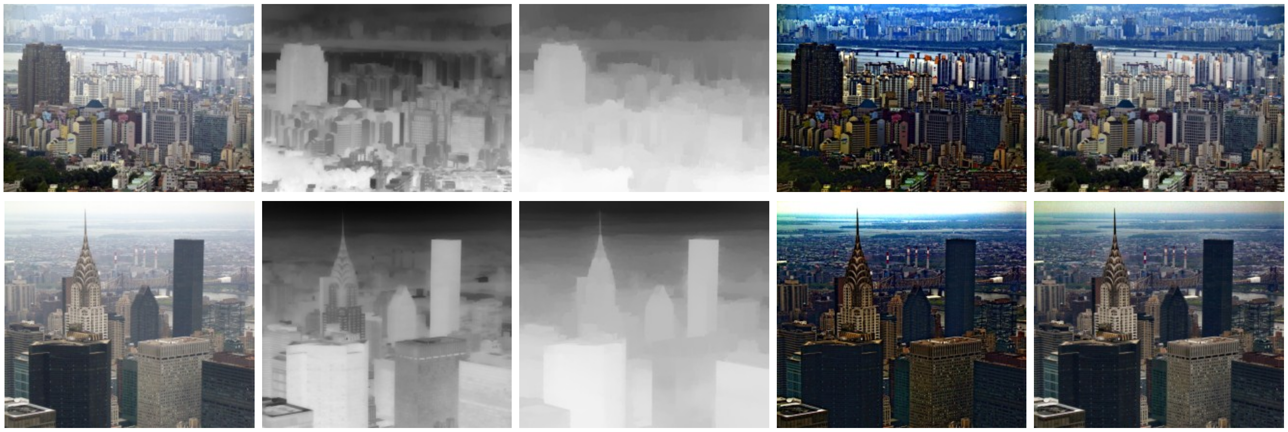
The image after haze removal still has low level of details and looks dim as in Fig 3(b). Hence, it is a necessary to enhance local contrast. We enhance the local contrast using multi-scale edge-preserving decompositions based on a WLS-filter [17] non-iteratively since it is easy to implement in the spatial domain. The decomposition layer consists of multiple layers with greater details at progressively finer scale. The layers are defined as follows, [17]

$$d^i = u_{i-1} - u_i, \quad \text{where } i = 1,\ldots,k. \tag{9}$$

The $u_0,\ldots, u_k$ denote progressively coarser versions of an input image by (7). We use a three level decomposition: a coarse base level and two detailed levels of the HSV lightness channel. The enhanced image is expressed as

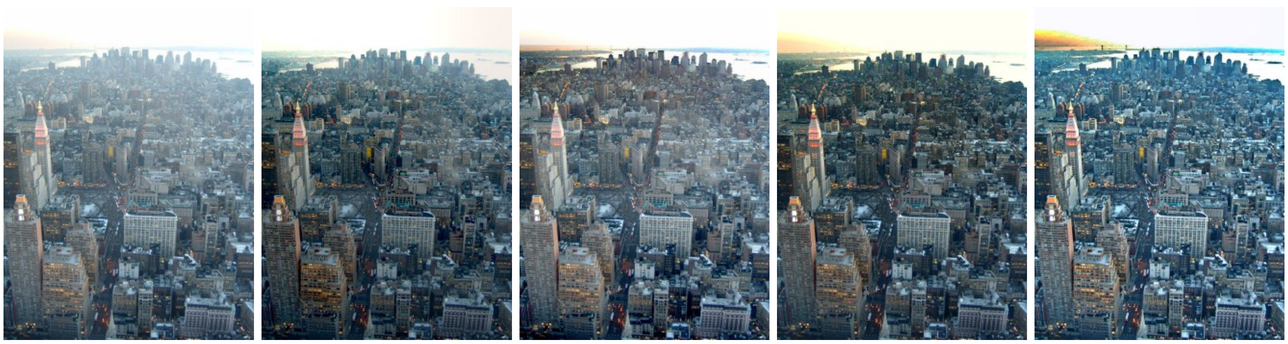
$$V_p = B + S(\delta, d_p^1) + S(\delta, d_p^2), \tag{10}$$

where $S(\cdot)$ is a sigmoid curve [17] and B is the base layer image containing fundamental luminance of the input image. Since recovered scene radiance is usually not as bright as the atmospheric light, recovered image looks dim. Therefore, we use a gamma corrected image ($\gamma = 0.75$) as the base layer to increase the exposure of recovered image. δ is the boosting factor to control the sigmoid curve. Since the objects far from the sensor seem to be blurred in a local region than those closer to the sensor, we use reversed transmission map rescaled from 0 to 10 as δ. From the boosting factor, we can compensate the loss of details while preventing over sharpening. Processed result from (10) is shown in Fig 3 (c).



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

Fig. 4. Comparison with Yu's work [10]. (a) Hazy image. (b) Estimated transmission map from Yu's work. (c) Estimated transmission map from our method. (d) Recovered scene radiance from (b). (e) Recovered scene radiance from (c).



(a)Hazy image (b)Fattal [6] (c)Kopf [19] (d) He [8] (e)Proposed method

Fig. 5. Comparison with other methods

5. EXPERIMENTAL RESULTS

We compared our method with conventional methods [6, 8, 10, 19]. Results are obtained from a desktop computer with Intel Core i7 2.67GHz CPU and 6GB RAM.

Fig. 4 compares the proposed method with Yu's method [10] using an urban scene. Yu's result as shown in Fig 4(b) indicates sporadic inaccuracies in the estimated transmission map. As apparent in Fig 4(c), the proposed method delivers better accuracy in the estimated transmission map compared to Yu's work. Furthermore, the proposed method provides better recovered overall results compared to Yu's work as shown in Fig. 4(d) and (e) respectively.

We also compared performance of the proposed method with other conventional methods whose results were uploaded on their webpages [6, 8, 19] in terms of Colorfulness [20] and Global Contrast Factor (GCF) [21] measure, respectively. Colorfulness is an evaluation indicator measuring the degree of color quality while GCF is an evaluation indicator capturing the degree of contrast quality. Although Fattal's method provides good performance in the region close to the sensor, the haze is not removed effectively in the other regions. While Kopf's and He's method respectively show reasonably good result, our proposed method provides distinctively superior performance as shown in Table 1. Furthermore, the proposed method takes about 4 seconds to refine the rough transmission of 640 x 480 image, while He's method takes about 60 seconds.

Table 1. Performance comparison of Fig. 5

	Colorfulness [20]	GCF [21]
Hazy image	255.96	5.01
Fattal [6]	387.01	5.89
Kopf [19]	390.67	6.65
He [8]	509.90	6.72
Proposed	890.08	8.80

6. CONCLUSIONS

In this paper, we proposed an effective and efficient de-hazing algorithm based on local contrast enhancement. The proposed method first estimates the rough transmission by DCP. Then, the rough transmission is refined by edge-preserving smoothing filter. Finally, the recovered scene radiance is enhanced using multi-scale tone manipulation. From the limited set of experiments, it successfully enhanced image qualities retaining color fidelity with faster refining time compared to the most recent conventional schemes known in literature.

In conclusion, when applied to practical systems such as a video based surveillance, the proposed algorithm is expected to successfully restore degraded contrast and color of images caused by air-light.

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