Fast Haze Removal for a Single Remote Sensing Image Using Dark Channel Prior

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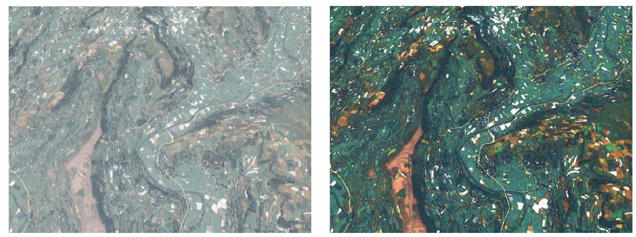
***Abstract*—Remote sensing images are widely used in various fields. However, they always suffer from the bad weather conditions which also affect their sufficient usage. In order to solve this problem, we propose a simple but effective method to remove haze from a single remote sensing image. Our work is based on the dark channel prior and a common haze imaging model. To eliminate artifacts, we use a low-pass Gaussian filter to refine the coarse estimated atmospheric veil. The experimental results show that our approach achieves good results with very little processing time.**

Keywords-remote sensing; image dehazing; dark channel; gaussian filter



(a) (b)

Figure 1. (a) Input image. (b) Our result.

I. Introduction

Remote sensing images are widely used in various fields for its advantages in a wealth of information, high spatial resolution and stable geometric location. Meanwhile, it has become the main method of acquiring spatial information. However, remote sensing is unusually vulnerable to the weather. Persistent haze imposes a significant effect on their fully use [1-3], as shown in Fig. 1(a). On the one hand, light reflected from the object surfaces attenuates due to the effect of absorption and scattering. On the other hand, owing to scattering process in the atmosphere, the atmospheric light is blended into the camera lens [4]. Under these two influences, remote sensing images taken in haze conditions lose contrast, saturation and color fidelity. Moreover, the haze degradation effect is highly correlated with the thickness of the haze and the distance from the camera lens to the observed object [5].

Haze removal (or dehazing) not only increases the effectiveness and availability of the remote sensing data, but also reduces the limitation of weather condition of aerial photography [3]. Therefore, it is of significance to remove the haze from the remote sensing images. However, haze removal is not a trivial task because it is an under-constrained problem if the input is only a single haze image.

Recently, haze removal has gained great progress since He et al. [6] had proposed the dark channel prior based on the statistics of outdoor haze-free images. On the basis of the dark channel prior, we propose a simple but effective method for haze removal. Unlike [6] which uses soft matting method to refine the transmission, we refine the atmospheric veil with a low-pass Gaussian filter, which can achieve good results and sufficient speed.

In this paper, we present a fast and physical-based method for single remote sensing image dehazing based on the work of He et al. [6]. It will be shown in the paper that our algorithm produces visual appealing results while using little processing time. The remaining paper is organized as follows. In section II, an analysis of haze imaging model is introduced. In section III, the method of our algorithm is described. In section IV, experimental results are shown. Finally, the discussion and conclusion are given in Section V.

II. Background

The haze imaging model widely used [7] in computer vision and computer graphics is expressed as:

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

where $\mathbf{x}$ indicates the position of a pixel, $\mathbf{I}(\mathbf{x})$ is the observed image intensity at pixel $\mathbf{x}$, $\mathbf{J}(\mathbf{x})$ is the scene radiance, $\mathbf{A}$ is the global atmospheric light, and $t(\mathbf{x})$ is the medium transmission describing the portion of the light that is not scattered and reaches the camera. It is an ill-posed problem, because it requires us to recover $\mathbf{J}$, $\mathbf{A}$ and t from only a single input image $\mathbf{I}$.

In (1), the first term $\mathbf{J}(\mathbf{x})t(\mathbf{x})$ on the right-hand side is called direct attenuation [4], and the second term is called airlight [4]. The direct attenuation indicates how the scene radiance is attenuated in the medium, and the airlight describes that the increasement of scene depth results in the shift of the scene color.

In a homogeneous atmosphere, the transmission is determined as

$$t(\mathbf{x}) = e^{-\beta d(\mathbf{x})}, \tag{2}$$

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where β is the atmospheric attenuation coefficient due to the scattering and $d(\mathbf{x})$ represents the distance from the position of pixel $\mathbf{x}$ to the observer. The transmission has a scalar value within (0,1) for each pixel, which indicates the depth information of the scene objects directly.

Theoretically, the scene radiance can be easily calculated when the transmission and the global atmospheric light are known, which can be written as

$$\mathbf{J}(\mathbf{x}) = \mathbf{A} - \frac{\mathbf{A} - \mathbf{I}(\mathbf{x})}{t(\mathbf{x})}. \quad (3)$$

III. Single Image Dehazing

In this section, we describe our method in detail. First we present a detailed description of dark channel prior of the haze-free outdoor images.

A. Dark Channel Prior

Here we describe the dark channel prior which was discovered by He et al. [6]. The dark channel prior is based on the following observation on outdoor haze-free images: In most of the nonsky patches, pixels in at least one color channel (r, g or b) have a low intensity value and close to zero. For an image $\boldsymbol{J}$, we define its dark channel J^{dark} as

$$J^{dark}(\mathbf{x}) = \min_{\mathbf{y}\in\Omega(\mathbf{x})}(\min_{c\in\{r,g,b\}} J^c(\mathbf{y})), \quad (4)$$

where J^c is a color channel of $\mathbf{J}$ and $\Omega(\mathbf{x})$ is a local patch centered at $\mathbf{x}$. If $\mathbf{J}$ is an outdoor haze-free image, the intensity of J^{dark} is very low and close to zero except for the sky region. This observation has been validated on a large set of images. He et al. [6] test this observation on 5,000 images which are haze-free landscape and cityscape and manually cut out the sky regions. It is found that 75 percent of the pixels in the dark channel have zero values, and the intensity of 90 percent of the pixels are below 25, which strongly supports the dark channel prior. The low intensity in the dark channel is mainly due to the fact that natural images are colorful and full of shadows.

Due to the additive airlight, pixels in sky and haze regions have high intensity in all color channels because the transmission t is low. Visually, the intensity of the dark channel is a rough approximation of the thickness of the haze.

B. Estimate the Atmospheric Light

As observed by Narasimhan and Nayar [8], the atmospheric light is best estimated in the most haze-opaque region. He et al. [6] choose the top 0.1 percent brightest pixels in the dark channel as the most haze-opaque region, and among these pixels, the one with highest intensity in the input image $\mathbf{I}$ is considered as the global atmospheric light. In this paper, we first compute the dark channel of the input haze image, then we estimate the global atmospheric light

$$\mathbf{A} = I(\mathbf{x}_k), \quad (5)$$

where $\mathbf{x}_k = \arg_{\mathbf{x}} max(I^{dark}(\mathbf{x}))$. That is to say, the pixel with the highest dark channel value in the input image $\mathbf{I}$ is considered as the global atmospheric light.

C. Estimate the Coarse Atmospheric Veil

We first define the atmospheric veil $V(\mathbf{x})$ [9,10] as follows

$$V(\mathbf{x}) = 1 - t(\mathbf{x}). \quad (6)$$

Since $t(\mathbf{x})$ is within (0,1), $V(\mathbf{x})$ is within (0,1) as well. The atmospheric veil presents the additive airlight to the scene imaging, and it is an increasing function of the object distance $d(\mathbf{x})$. Thus, the haze imaging model (1) can be rewritten as

$$\mathbf{I}(\mathbf{x}) = \mathbf{J}(\mathbf{x})t(\mathbf{x}) + \mathbf{A}V(\mathbf{x}). \quad (7)$$

In (7), we normalize the haze imaging model by dividing the global atmospheric light A^c in each color channel separately, which is expressed as:

$$\frac{I^c(\mathbf{x})}{A^c} = \frac{J^c(\mathbf{x})}{A^c}t(\mathbf{x}) + V(\mathbf{x}). \quad (8)$$

However, $\frac{I^c(\mathbf{x})}{A^c}$ will be greater than 1 for the pixels whose intensities are higher than the atmospheric light $\mathbf{A}$. So we further restrict the normalized image $\frac{I^c(\mathbf{x})}{A^c}$ into [0,1] with linear stretch method.

Therefore, the haze imaging model can be rewritten as

$$\frac{\mathbf{I}(\mathbf{x})}{\mathbf{A}} = \frac{\mathbf{J}(\mathbf{x})}{\mathbf{A}}t(\mathbf{x}) + V(\mathbf{x}). \quad (9)$$

According to (9), the atmospheric veil $V(\mathbf{x})$ is subjected to two constraint [10]:
1) $V(\mathbf{x})$ is positive;
2) $V(\mathbf{x})$ could not be higher than the min color component of $\frac{\mathbf{I}(\mathbf{x})}{\mathbf{A}}$, which is $V(\mathbf{x}) \leq \frac{\mathbf{I}(\mathbf{x})}{\mathbf{A}}$.

First we assume that the atmospheric veil and transmission in a local patch $\Omega(\mathbf{x})$ is constant. Denote this atmospheric veil and transmission as $\tilde{V}(\mathbf{x})$ and $\tilde{t}(\mathbf{x})$ respectively, then we take the minimum operation to both three color channels and the local patch on the haze imaging model (9):

$$\min_{\mathbf{y}\in\Omega(\mathbf{x})}(\min_{c\in\{r,g,b\}} \frac{I^c(\mathbf{y})}{A^c}) = \tilde{t}(\mathbf{x}) \min_{\mathbf{y}\in\Omega(\mathbf{x})}(\min_{c\in\{r,g,b\}} \frac{J^c(\mathbf{y})}{A^c}) + \tilde{V}(\mathbf{x}). \quad (10)$$

According to the dark channel prior, the dark channel of $\mathbf{J}(\mathbf{x})$ is close to zero:

$$J^{dark}(\mathbf{x}) = \min_{\mathbf{y}\in\Omega(\mathbf{x})}(\min_{c\in\{r,g,b\}} J^c(\mathbf{y})) = 0. \quad (11)$$

As A^c is always positive, this leads to:

$$\min_{\mathbf{y}\in\Omega(\mathbf{x})}(\min_{c\in\{r,g,b\}} \frac{J^c(\mathbf{y})}{A^c}) = 0. \quad (12)$$

Putting (12) into (10), we can extract the atmospheric veil simply by:

$$\tilde{V}(\mathbf{x}) = \min_{\mathbf{y}\in\Omega(\mathbf{x})}(\min_{c\in\{r,g,b\}} \frac{I^c(\mathbf{y})}{A^c}). \quad (13)$$

In this paper, we only take the minimum operation on the three color channels to get the coarse atmospheric veil, which is

$$\tilde{V}(\mathbf{x}) = \min_{c\in\{r,g,b\}} \frac{I^c(\mathbf{x})}{A^c}. \quad (14)$$

D. Refine the Atmospheric Veil using Gaussian Filter

As we take the minimum operation of image $\frac{I^c(\mathbf{x})}{A^c}$ to estimate the atmospheric veil $V(\mathbf{x})$, $V(\mathbf{x})$ could not be continuous even if there is no abrupt depth discontinuities occur. Therefore, it is necessary to take smooth operation on $V(\mathbf{x})$, otherwise it will cause halo artifacts in the restored image.

In this work, we use a low-pass Gaussian filter to refine the atmospheric veil. Gaussian filter is a nonlinear filter that smooths the images. We smooth the atmospheric veil using a low-pass Gaussian filter, the refined atmospheric veil $V(\mathbf{x})$ can be expressed as

$$V(\mathbf{x}) = \frac{1}{W^g} \sum_{\mathbf{y} \in S} G_\sigma(\|\mathbf{x} - \mathbf{y}\|)\tilde{V}(\mathbf{y}), \tag{15}$$

where W^g is the sum weight of the local patch centered at pixel $\mathbf{x}$

$$W^g = \sum_{\mathbf{y} \in S} G_\sigma(\|\mathbf{x} - \mathbf{y}\|). \tag{16}$$

Here G is a Gaussian function, and the parameter σ represents the size of the neighborhood used to smooth a pixel. According to the low-pass Gaussian filter, those pixels near the centered pixel $\mathbf{x}$ will get large weight.

With the refined atmospheric veil, the transmission can be easily calculated according to (6)

$$t(\mathbf{x}) = 1 - V(\mathbf{x}). \tag{17}$$

E. Recover the Haze-free Image

With the obtained global atmospheric light and transmission, the scene radiance can be recovered. However, since the coarse atmospheric veil is estimated using the minimum component on the image $\frac{\mathbf{I(x)}}{\mathbf{A}}$, the difference between the image $\frac{\mathbf{I(x)}}{\mathbf{A}}$ and the coarse atmospheric veil is close to zero with great probability. Moreover, the transmission of the sky in the infinite distance is close to zero, which makes the direct attenuation $\mathbf{J}(\mathbf{x})t(\mathbf{x})$ close to zero. Thus, the recovered scene radiance is prone to noise. In order to overcome this problem, we use a lower bound t_0 to restrict the transmission $t(\mathbf{x})$ and k to keep a small amount of haze for the distant objects. Therefore, the scene radiance $\mathbf{J}(\mathbf{x})$ can be restored by

$$\mathbf{J}(\mathbf{x}) = \mathbf{A} \times \frac{\mathbf{I}(\mathbf{x})/\mathbf{A} - kV(\mathbf{x})}{max(t(\mathbf{x}), t_0)}. \tag{18}$$

Since the image after haze removal always becomes dark, we use piecewise nonlinear stretch method to increase the contrast.

Thus, the scene radiance in our paper is restored as in Algorithm 1.

Algorithm 1 restore the scene radiance

Step 1: Input an original haze image $\mathbf{I}(\mathbf{x})$ and compute its dark channel image as

$$I^{dark}(\mathbf{x}) = \min_{\mathbf{y} \in \Omega(\mathbf{x})} \left(\min_{c \in \{r,g,b\}} I^c(\mathbf{y}) \right),$$

where $I^c(\mathbf{x})$ represents a color channel of the input image, $\Omega(\mathbf{x})$ is a local patch centered in pixel $\mathbf{x}$ and the patch size in our paper is 4×4.

Step 2: Estimate the global atmospheric light

$$\mathbf{A} = \mathbf{I}(\mathbf{x}_k),$$

where

$$\mathbf{x}_k = \arg_{\mathbf{x}} max(I^{dark}(\mathbf{x})).$$

Step 3: Normalize the haze imaging model by A^c in each color channel

$$\frac{I^c(\mathbf{x})}{A^c} = \frac{J^c(\mathbf{x})}{A^c} t(\mathbf{x}) + V(\mathbf{x}).$$

Then restrict the normalized image $\frac{I^c(\mathbf{x})}{A^c}$ into [0,1] with linear stretch method.

Step 4: Estimate the atmospheric veil roughly as

$$\tilde{V}(\mathbf{x}) = \min_{c \in \{r,g,b\}} \frac{I^c(\mathbf{x})}{A^c}.$$

Step 5: Refine the coarse atmospheric veil using a low-pass Gaussian filter

$$V(\mathbf{x}) = \frac{1}{W^g} \sum_{\mathbf{y} \in S} G_\sigma(\|\mathbf{x} - \mathbf{y}\|)\tilde{V}(\mathbf{y}),$$

where W^g is the sum weight of the local patch centered at pixel $\mathbf{x}$

$$W^g = \sum_{\mathbf{y} \in S} G_\sigma(\|\mathbf{x} - \mathbf{y}\|).$$

Then the transmission is

$$t(\mathbf{x}) = 1 - V(\mathbf{x}).$$

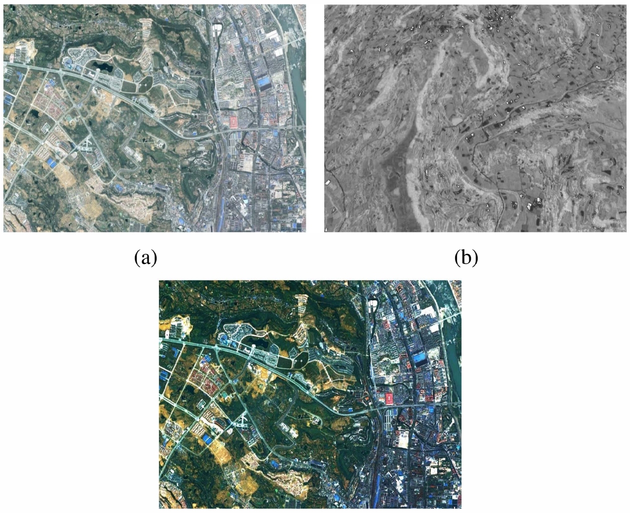
Step 6: Restore the scene radiance

$$\mathbf{J}(\mathbf{x}) = \mathbf{A} \times \frac{\mathbf{I}(\mathbf{x})/\mathbf{A} - kV(\mathbf{x})}{max(t(\mathbf{x}), t_0)}.$$

IV. Experiments Results

We have done several experiments to verify the validity of our algorithms. For an image of size 600×400, it takes 0.565s to process on a PC with a 3.2GHz Intel Core i5 Processor using Matlab 2010a. We have also tested our approach with C++. It turns out that it only needs 31ms to process a 600×400 image in C++. And the dehazed images are visually appealing.

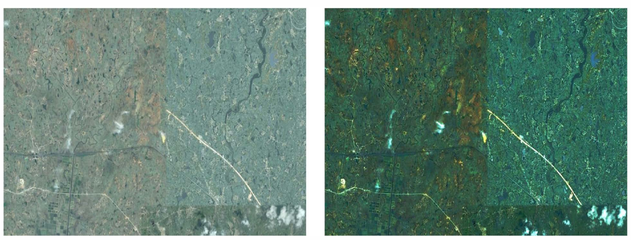
For remote sensing images, our algorithm gets appealing results. We first manually cut out several haze images from the Google Earth, then use our approach to remove the haze on these remote sensing images. The results are showed in Fig. 1, Fig. 2, Fig. 3 and Fig. 4. Since the haze in remote sensing images is homogeneous, the restored images look natural and the color remains consistent with the original ones. Comparing Fig. 1, Fig. 2, Fig. 3 and Fig. 4 before and after haze removal, the effect of our approach is convincible.



(a) (b)

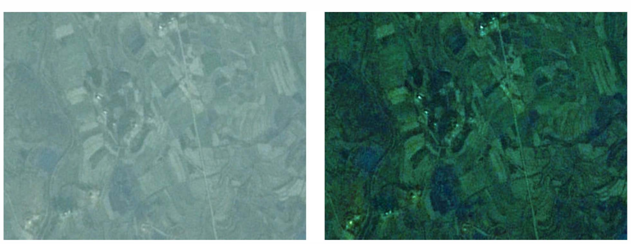
(c)

Figure 2. (a) Input image. (b) The transmission. (c) Our result.



(a) (b)

Figure 3. (a) Input image. (b) Our result.



(a) (b)

Figure 4. (a) Input image. (b) Our result.

V. Conclusion

Persistent haze imposes a heavy problem on remote sensing images' full usage. In this paper, we present a simple but effective method for single remote sensing image haze removal. Based on the dark channel prior, we can easily extract the global atmospheric light and roughly estimate the atmospheric veil with the dark channel of the input haze image. We then refine the atmospheric veil using a low-pass Gaussian filter. Our technique has been tested for several remote sensing images. Comparing the original haze images with the haze removal ones, the effect of our approach is convincible. Moreover, our approach enjoys sufficient speed.

In most cases, our approach can achieve good results. However, when the images have dense and heterogeneous haze, the results obtained will have color distortion especially in the bright regions and loss of details. Our future work is to find a fast and effective way for these images and test our method for videos.

VI. Acknowledgment

The work was supported by the National Natural Science Foundation of China under the Grants 61273245, 60975003 and 91120301, the 973 Program under the Grant 2010CB327904, the open funding project of State Key Laboratory of Virtual Reality Technology and Systems, Beihang University (Grant No. BUAA-VR-12KF-07), the Beijing Natural Science Foundation (Non-negative Component Analysis for Hyperspectral Imagery Unmixing) under the Grant 4112036, and Program for New Century Excellent Talents in University of Ministry of Education of China under the Grant NCET-11-0775. The work was also supported by Beijing Key Laboratory of Digital Media, Beihang University, Beijing 100191, P.R. China.

References

[1] X. Wen, X. Yang, "Haze removal from the visible bands of CBERS remote sensing data," 2009 International Conference on Industrial and Information Systems, DOI 10.1109/IIS.2009.58.

[2] Y. Zheng, H. Li, H. Gu, H. Feng, "Research on the haze removal method and parallel implementation for HJ-1 satellite data," IEEE, 2010.

[3] J. Yang, Y. Zhang, X. Zhou, G. Dong, "Using dark channel prior to quickly remove haze from a single image," Geomatics and Information Science of Wuhan University, vol. 35, Nov. 2010(in Chinese).

[4] H. Koschmieder, "Theorie der horizontalen sichtweite," Beitr. Phys. Freien Atm., vol. 12, pp. 171-181, 1924.

[5] S. Wang, H. Wan, L. Zeng, X. Peng, "Haze removal methods of remote sensing image using dark channel prior," Journal of Geomatics Science and Technology, vol. 28, 2011(in Chinese).

[6] K. He, J. Sun, and X. Tang, "Single image haze removal using dark channel prior," IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 33, Dec. 2011.

[7] S.G. Narasimhan and S.K. Nayar, "Vision and the atmosphere," Int'l J.Computer Vision, vol. 48, pp. 233-254, 2002.

[8] S.G. Narasimhan and S.K. Nayar, "Contrast restoration of weather degraded images," IEEE Trans. Pattern Analysis and Machine Intelligence, vol. 25, no. 6, pp. 713-724, June 2003.

[9] Tarel, J.P., Hautiere, N. "Fast visibility restoration from a single color or gray level image," IEEE International Conference on Computer Vision, 2009.

[10] J. Yu, D. Li, Q. Liao, "Physics-based fast single image fog removal," Acta Automatica Sinica, vol. 37, Feb. 2011(in Chinese).