Atmospheric scattering-based multiple images fog removal

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***Abstract*—Current video and image systems are typically of limited use for their poor visibility and contrast caused by the presence of fog, haze and mist. However, the local hazy areas of these images are often interested in and required their sharpness. In this paper, a novel fast haze removal algorithm from multiple images in uniform bad weather conditions which bases on the atmospheric scattering model is proposed. The key idea is to establish an overdetermined system by modeling the hazy images and corresponding images taken in clear days so that the transmission and global airlight can be obtained. Then the two parameters solved from the equations are applied to the local hazy area. Experimental results demonstrate that the proposed algorithms remove haze effectively and achieve accurate restoration.**

Keywords-atmospheric scattering model; transmission;scene depth;airlight

I. INTRODUCTION

In foggy scenes, the presence of aerosols has substantial effects on the images in which surface colors become faint and contrasts are reduced. Such degraded images often lack visual vividness and appeal, but many applications such as video surveillance, face recognition and intelligent vehicle monitoring require robust detection of image features. Hence, it is highly desired to remove haze effects from images. All established dehazing methods can be divided into two categories: foggy image enhancement based on image processing and foggy image restoration based on atmospheric scattering model. The foggy image enhancement improves the quality of images for human viewing without knowledge about the source of degradation. Therefore it is widely applied to foggy images. Although these methods can improve images' contrast and enhance images' detail, they also brought noise enhancement. The foggy image restoration considers the process of degradation—atmospheric scattering model[1],[2],[3]. Then inverse the process, compensate the distortion and obtain the estimation of haze-free images finally. There are two kinds of methods based on this scattering model: single image and multiple images haze removal. The algorithm proposed in this paper belongs to the latter. Single image defogging methods remove haze by making use of various assumption or prior to generate cost function and constraint equation. Tan [11] develops a cost function in the framework of random fields relied on two observations that clear-day images have higher contrast than foggy images and the airlight tends to be smooth. But the results may contain halo effects near the depth discontinuities and tend to have larger saturation for its neglect of physical model. Fattal [7] assumes that the transmission and surface shading are statistically uncorrelated in local patch. This approach is physically sound and can produce good results, but may be unreliable when dense fog covers the surface's color information. He et al. [8] propose the dark channel prior that the haze-free outdoor images within a local patch contain some pixels which have very low intensities in at least one color channel. Soft matting is utilized to refine the transmission. However, the alpha map and the transmission map are not in accordance with each other in physics. When the surface color of the object is similar to the airlight, it is invalid. Tarel et al. [12] infer the atmospheric veil by maximizing it instead of seeking to infer the depth-map. This algorithm is faster than methods described above. He uses the Median of Median along Lines filter [13] to preserve edges and corners. But the results will be poor if the parameters are not properly controlled.

Restoring scene colors and contrasts from a single image is usually under constrained. Therefore there are many methods have been proposed based on multiple images, which can be divided into two kinds. Some methods [6] require multiple input images of the same scene to be taken under different haze conditions. Other methods [2], [4], [5] obtain the multiple images by varying imaging optics. In practical situations, it is difficult to achieve these conditions.

In this paper, novel ideas are developed after the study of dehazing algorithms. a) Restoring the colors and contrasts of different scenes taken under the same haze conditions. b) The known conditions are near and far images, including the foggy images and corresponding clear-day images. We try to recover the clear scene colors from the foggy image whose scene depth between the near and far. The obvious advantage of the proposed algorithm is its speed and the possibility to deal with both color images and gray-level images.

This paper is organized as follows. It mainly describes the atmospheric scattering model in section 2. And section 3 gives a detailed interpretation of the proposed algorithm. In section 4, a necessary comparison and analysis between the proposed method and other methods are presented. Section 5 is the concluding part.

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II. ATMOSPHERIC SCATTERING MODEL

The effects that suspended particles existed in atmosphere have on light can be broadly classified into three categories: scattering, absorption and emission. And scattering plays a major role in the effects. We summarize two models of atmospheric scattering:

- Attenuation, light reflected from the object surface is attenuated due to scattering by the aerosol suspended in gas.
- Airlight, environmental illumination of the scene due to sunlight, skylight and reflected ground light are scattered because of particles in the atmosphere cause the apparent brightness of a scene point. The model is shown in Fig.1.

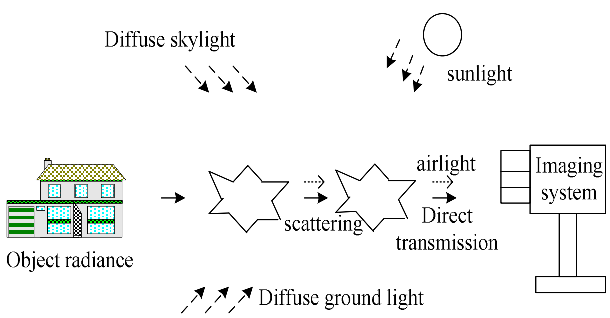

Figure 1. *The atmospheric scattering model*

The atmospheric scattering model commonly used in computer vision and computer graphics is as follows:

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

where $I(x)$ is the observed image intensity at pixel x, $J(x)$ is the scene radiance. Generally, we can regard fog near ground as homogeneous. The transmission $t(x)$ represents the ability that light interactions with the atmosphere can be expressed as:

$$t(x) = e^{-\beta(\lambda)d} \; . \tag{2}$$

It describes the part of the light that is not scattered and reaches the camera. $\beta(\lambda)$ denotes the scattering coefficient. According to Rayleigh's law of atmospheric scattering, we know about the relationship between the scattering coefficient β and the wavelength λ [3]:

$$\beta(\lambda) \propto \frac{1}{\lambda^{\gamma}} \; . \tag{3}$$

where $0 \le \gamma \le 4$, and γ depends on particles size suspended in the gas. In clear days, $\gamma = 4$. The molecules' scattering is selective, and the blue wavelengths are scattered more compared to other visible wavelengths. On the other hand, fog and haze scatter all visible wavelengths more or less the same way [11], $\gamma \approx 0$. In this paper, we assume the scattering coefficient $\beta(\lambda) = \beta$ to be constant since the camera usually has narrow spectral bands in most cases. d is the distance between the object and the imaging system. We can infer from (2) that light reflected from the object surface is attenuated exponentially with the scene depth d. A is the global atmospheric light and can be regarded as a constant if images are taken under the same weather condition. The first term $J(x)t(x)$ on the right hand side of (1) is called direct attenuation, which describes the scene radiance and its attenuation in the atmosphere. The latter term $A(1 - t(x))$ is called airlight [12], which is the addition of a white atmosphere veil.

III. MULTIPLE IMAGES DEHAZE OF DIFFERENT SCENES

It is known from (1) that the process of image degradation due to bad weather is exponential in the depths of the scene points. Hence, it is ill-posed to restore scene colors and contrasts from a single image. Recently, it has been shown that multiple images of the same scene taken under different weather conditions [9] or multiple images taken by varying imaging optics [10] can be used to break the ambiguities in deweathering.

In this paper, a physics-based method is presented to restore contrast of a scene from two or more images taken in uniform bad weather conditions. Above all, images of a scene taken under clear weather and foggy or hazy weather are considered. The details are as follows:

A. A. foggy image restoration of different scenes under the same scene depth

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

As discussed in section 1 that the scattering coefficient for fog and dense haze remains more or less constant over the visible spectrum. In this derivation, the transmission $t(x)$ merely depends on the scene depth d. We claim that the global atmospheric light A and transmission $t(x)$ can be counted as constants if the scene depth is more or less and foggy images are taken under the same weather conditions. This claim is the heart of our paper because all the following methods proposed are based on it.

1) foggy image restoration under the same scene depth

The hazy images and corresponding clear-day images of the same scene 'a' are considered as reference pictures taken by imaging systems. It is supposed to do image registration if they are not aligned and choose the common part as the reference pictures. This is seen as an initialization step that needs to be done before applying the contrast restoration algorithm of the following. Every pixel's depth is assumed to be more or less and one pixel decides one equation. Theoretically, two unknown numbers can be solved by two equations. However, the scene depth is not absolutely equal; this may induce inaccuracy and noise if only two equations are established. So the methods proposed in this paper are as follows: Every pixel decides one constraint equation, and all of the pixels of the whole image establish an overdetermined system. Assume there are $m \times n$ pixels in one reference image and there will be $m \times n$ equations.

$$\begin{cases} I(x_1) = J(x_1)t + A(1-t) \\ I(x_2) = J(x_2)t + A(1-t) \\ \quad\cdots\cdots \\ I(x_{m\times n}) = J(x_{m\times n})t + A(1-t) \end{cases} . \tag{4}$$

Then the two parameters A and t can be solved from the overdetermined system by least squares algorithm. This method is able to reduce inaccuracy to a great extent as well as noise which may appear in the restored colors.

In outdoor surveillance applications, video cameras capture the different scene 'b' with the same depth and weather condition as scene 'a'. Recall that the transmission t merely depends on the scene depth d, which means the scene 'b' has the same transmission t as scene 'a'. In addition, the global atmospheric light A is also equal because of the same weather conditions. So the two parameters t and A solved from scene 'a' can be applied to foggy images of scene 'b'. The restoration of the original image colors of scene 'b' can be performed by solving (5) with respect to $J(x)$:

$$J(x) = \frac{I(x) - (1-t(x))A}{t(x)} . \tag{5}$$

Consider the characteristics of images in video surveillance systems: scenes are simple, which is suitable for choosing reliable reference objects. Video cameras capture the same scene over long periods of time during which the weather may change. So it's convenient to acquire reference images, including images of a scene taken under clear weather and foggy or hazy weather. The proposed method can be further used for many applications such as outdoor surveillance and intelligent vehicles et al. Suppose that some information in a local patch is what we are interested in when dealing with a foggy image. Meanwhile, the corresponding clear-day image is unknown. The two parameters $t(x)$ and A can be obtained by using other regions of the scene and applied to the foggy local patch. Fig.2 illustrates vividly the process of our work.

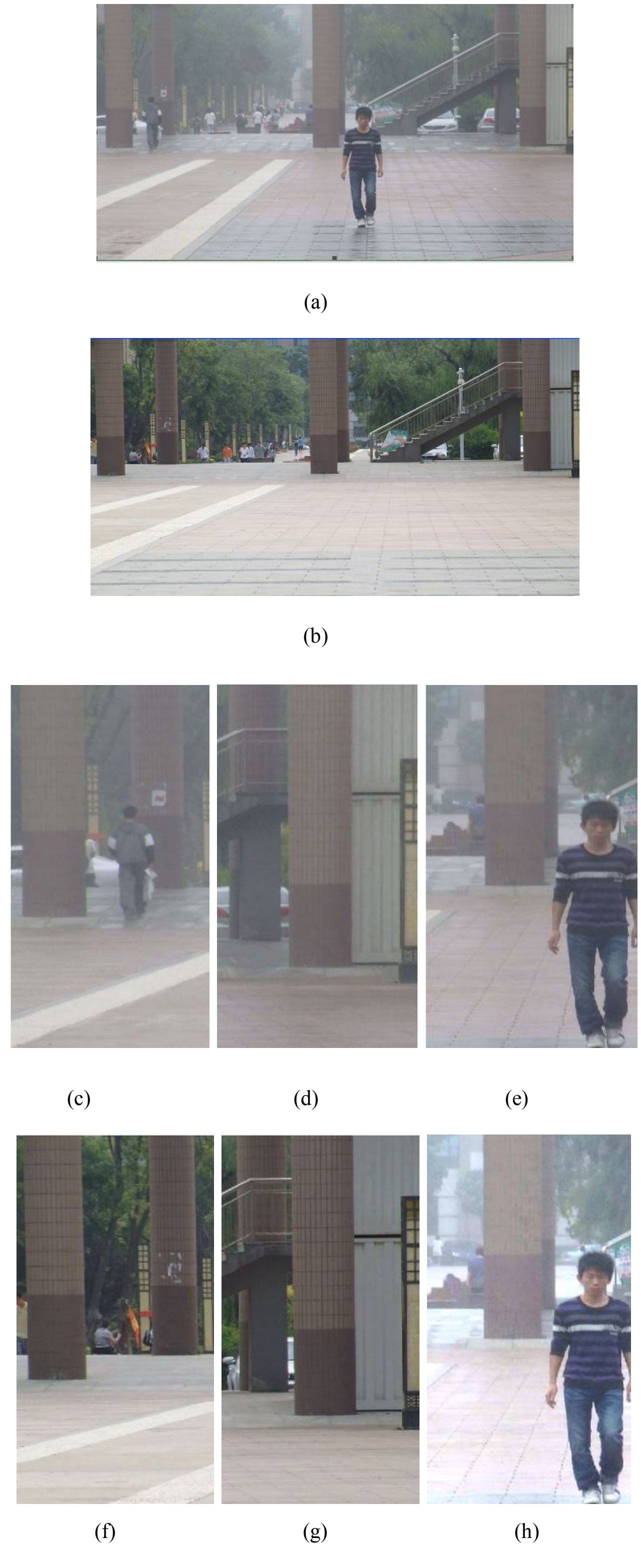

Figure 2. (a) The foggy image (b)The clear-day image (c)The reference image 1 (d)The reference image 2 (e)The input image (f)The clear-day image 1 (g) The clear-day image 2 (h)The reatored image

2) Calculating the parameters

Least squares describes a frequently used approach to solve overdetermined or inexactly specified systems of equations in an approximate sense. Instead of solving the equations exactly, we seek only to minimize the sum of the squares of the residuals. Let x be the independent variable and let y denote an unknown function of x that we want to approximate. Assume there are m values of y measured at specified values of x:

$$y = f(x_1, x_2, \ldots x_m; a_0, a_1, \ldots a_n). \tag{6}$$

where $a_0, a_1, \ldots a_n$ are the $n+1$ parameters that needed to be solved, and there are more equations than unknowns, that is $m > n+1$. The purpose of the overdetermined system is to calculate the $n+1$ parameters from m equations.

The model adopted in this paper is a linear fitting of the least squares. The relationship between y and x is: $y = a_0 + a_1 x$. The parameters a_0 and a_1 should make $s(a_0, a_1) = \sum_{i=1}^{m} (y_i - a_0 - a_1 x_i)^2$ have the minimum value. Thus the parameters are obtained:

$$\begin{aligned} a_1 &= \left(\sum_{i=1}^{m} x_i y_i - m\bar{x}\bar{y}\right) / \left(\sum_{i=1}^{m} x_i^2 - m\bar{x}^{-2}\right) \\ a_0 &= \bar{y} - a_1 \bar{x} \end{aligned} \tag{7}$$

Similarly, we regard $t(x)$ as a_0, $A(1-t(x))$ as a_1, $I(x)$ as y and view $J(x)$ as x. The two parameters of atmospheric scattering model are acquired from (7).

Aware of the limitations that all of images participated in this algorithm must have the same scene depth and many images can't meet the condition, we thus now introduce another method.

B. foggy image restoration of different scenes under different scene depths

The method proposed here still needs meet some conditions. The known conditions are near and far images' intensities, including the foggy images and corresponding clear-day images. Every image should be at the same depth, which guarantees every pixel's transmission $t(x)$ in one image is equal. All of the foggy images are taken under the same weather condition, which guarantees the global atmospheric light A is roughly equally. The purpose is to recover the clear scene colors from the foggy image whose scene depth is between the near and far.

1) Basic principles of different depth information

The foggy images are known with scene depth of d_1, d_2, d_3 taken in uniform bad weather conditions, where $d_1 < d_2 < d_3$. Note, this does not mean that actual scene depths have to be known. The corresponding clear-day images with scene depth d_1, d_3 are also known conditions. The transmission t is the nonlinear function of βd according to (2). βd is called optical depth. Apply the algorithm proposed in section 2.1 to images of depth d_1, d_3, then we can obtain the parameters A_1, A_3, t_1, t_3. It is easy to infer the optical depth βd_2 based on the relationship of d_1, d_2, d_3, which will be discussed later. As long as estimate the values of t and A at depth d_2, the colors and contrasts will be ultimately restored. The implementation flow chart is shown in Fig.3.

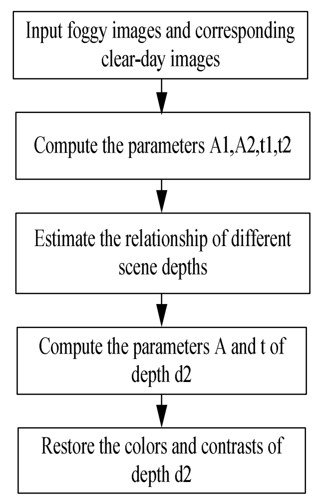

Figure 3. The flow chart of this method

2) Estimating the depth

According to (2), we have:

$$\beta d = -\ln t \quad . \tag{8}$$

Hence, the optical depth of d_1, d_3 can be obtained:

$$\begin{cases} \beta d_1 = -\ln t_1 \\ \beta d_3 = -\ln t_3 \end{cases} .$$

But how to infer the optical depth βd of the scene depth d_2 from its relationship with d_1, d_3? In a purely empirical manner, we tried several linear and nonlinear functions on a range of test images. The function that provided the best overall color restoration is:

$$\beta d = \beta d_1 + k\beta(d_3 - d_1) \ . \tag{9}$$

where $k \in (0,1)$ is a constant can be estimated from the actual distance relationship between d_2 and d_1 , d_3 . Then substituting (9) into (2), we estimate the transmission t .

This method is based on the algorithm proposed above. Least squares is still the main approach to solve overdetermined system. Of course, the estimation of depth d_2 in this paper is not the only way. There are many other methods, such as curve-fitting and so on. It depends on the actual conditions.

3) Estimating the global atmospheric light A

Overdetermined system is separately established at depth d_1 , d_3 , which can obtain two global atmospheric light A_1 , A_3 . The two values should be equal in theory under the same weather condition. However, they are different because of deviation's existence. We get the final A by averaging A_1 and A_3 .

IV. Experimental results and analysis

In order to verify the performance of the proposed algorithm, the comparison between the approach and previous methods [9], [13] will be given.

A. foggy image restoration under the same scene depth

In Fig.4, (a) the input image, (b) Tarel's result with p=0.7, Sv=81，balance=1.0, (c) He's result, (d) the result of this paper. We can see Tarel's result suffers from incorrect halo artifacts around the depth discontinuities. He's result seems doesn't remove completely. The result in this paper recovers the colors without sacrificing the fidelity.

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

Figure 4. foggy image restoration under the same depth

B. foggy image restoration under different scene depths

In Fig.5, (a) the input image, (b) Tarel's result with p=0.95, Sv=61, (c) He's result, (d) the result of this paper. As can be seen, the results of (b) and (c) have over-saturated colors. The result of this paper removes haze effectively and restores actual scene colors and contrasts.

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

Figure 5. foggy image restoration under different depths

V. CONCLUSIONS

In this paper, a novel haze removal algorithm based on physics model by solving overdetermined systems is proposed. Experimental results verified the effectiveness of this approach. The obvious advantage is its speed and the possibility to deal with both color images and gray-level images. However, all of the conditions must be satisfied in order to validate the algorithm.

ACKNOWLEDGMENT

This work is supported in part by the Specialized Research Fund for the Doctoral Program of Higher Education (No.20070151014).

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