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Single image dehazing in inhomogeneous atmosphere

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ABSTRACT

In hazy days, the contrast is reduced with the distance, which hinders the outdoor surveillance system from working properly. Considering the variation of aerosols concentration in inhomogeneous atmosphere and the relation between the attenuation coefficient and aerosols, we propose a more valid model for the attenuation coefficient than the existing one. In this paper, we propose an effective and robust algorithm based on dark channel prior and our optical model in inhomogeneous atmosphere to remove the haze effect from a single input image. In the proposed approach, we refine the coarse transmission map using guided filter, which is very effective while achieving fast speed. Based on our automatically sky region detection, we adjust the refined transmission, with which we can effectively overcome the color distortion in sky regions similar to the atmospheric light. We demonstrate that our method yields similar or even better results than the state-of-the-art techniques while performing fast. Moreover, our simple technique can be applied to most scenes plagued by haze and achieves visually compelling results.

1. Introduction

In foggy and hazy days, light reflected from an object is scattered and absorbed due to the substantial presence of molecules and aerosols suspended in the atmosphere. With the deterioration of the air quality, haze phenomenon frequently occurs. Most Chinese cities have witnessed an increasing occurrence of haze in recent years. Due to the effect of dense haze, the transparency of the atmosphere and the visibility are reduced significantly, which will cause considerable disruption to traffic and people's daily lives. Persistent haze obscures the view, making the vehicles, cyclists, and pedestrians move slowly, which often leads to massive traffic jams. In this paper, instead of exploring how to completely wipe out the haze effect from the weather, we focus our attention on how to perfectly remove haze from single hazy images.

In haze weather, images taken in outdoor environment will be severely degraded. Such degraded images are often characterized by poor contrast and low vividness of the scene. The degradation of outdoor images significantly influences the reliability of outdoor vision applications, such as video-surveillance systems, traffic monitoring system and intelligent vehicle. The existence of haze imposes a challenging problem in algorithms that designed for images captured in clear weather. On the other hand, weather is affected by haze at an increasing rate. Moreover, the image dehazing algorithm can also be applied to images captured in underwater environments [1]. Therefore, it is urgent and significant to find an effective algorithm to remove the haze effect from images.

The effect of haze increases with the distance, which makes image dehazing a quite challenge problem. Several researchers have been working on methods of haze removal and proposed several methods by using multiple images. In [2–4], a haze-free image is recovered using two or more images of the same scene taken under different weather conditions. By using multiple polarization-filtered images taken at different orientations of the polarizing filter [5,6], the effects of haze can be successfully removed from hazy images. Since our goal is to remove the effects of haze from a single image, such multiple images based techniques are not applicable for our needs.

Widespread attention has been paid to remove haze effects from a single hazy image. Recently, several successful methods for single image dehazing have been proposed. Tan [7] removes haze based on an observation that clear-day images have more contrast than hazy images. The contrast is greatly enhanced, while the recovered images are mostly oversaturated and even deviate from the scene's original colors. Moreover, this algorithm could produce halo artifacts at depth discontinuities. Fattal [8] assumes that the surface shading and medium transmission are locally statistically uncorrelated, and recovers haze-free scene contrast. This approach is physically sound and the recovered results are visually appealing, but it could be invalid when the haze is thick or the assumption fails.

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By observing the characteristics of outdoor haze-free images, He et al. [9] propose a dark channel prior, with which dehazing operation can be easily carried out. Although the results obtained by these methods seem visually compelling, their processing speeds are all slow, which hinders surveillance systems from proper functioning. In addition, the attenuation coefficient in these methods is assumed to be constant, while in the actual atmosphere, it changes as a function of altitude, which we will discuss later.

In the present work, we propose an effective and robust algorithm for image dehazing which is based on dark channel prior, originally proposed by He et al. [9]. In most cases, He et al. [9] can recover high-quality haze-free images. However, it could fail when processing haze images containing scene objects similar to the atmospheric light. Color distortions appear in sky regions similar to the atmospheric light. Besides, the recovered results contain halo artifacts in abrupt depth discontinuities. This lies in their haze imaging model, which assumes the attenuation coefficient is constant. Yet in the actual atmosphere, the attenuation coefficient is not a constant but varies with altitude. In this paper, considering changes of the attenuation coefficient, we first present an optical model in inhomogeneous atmosphere. To satisfy this optical model, we adjust the transmission with some strategy. Thus, we are able to handle the color distortions in sky regions and produce high-quality recovered results. Contributions of our paper include:

(1) We take the inhomogeneous atmosphere into consideration and propose a new model for the attenuation coefficient in the inhomogeneous atmosphere, which differs from the constant attenuation coefficient generally assumed in homogeneous atmosphere.
(2) In order to get the physically valid transmission, we first propose a simple but effective approach to roughly detect the sky regions, taking advantage of the dark channel images of the original hazy images.
(3) With the estimated sky region, we adjust the refined transmission. Our adjusted transmission describes the optical model in inhomogeneous atmosphere more accurately. Therefore, we are able to overcome the color distortion in sky regions similar to the atmosphere light and greatly enhance the image contrast.

The remaining of the paper is organized as follows. In Section 2, a detailed analysis of optical model is introduced. The method of our image dehazing algorithm is described in Section 3. Experimental results and evaluation are shown in Section 4. Finally, in Section 5, we conclude the paper and discuss some possible future work.

2. Background

2.1. Optical model in homogenous atmosphere

The widely used optical model in computer vision and computer graphics [2,9,10] is as follows

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

Here, $\mathbf{I}(\mathbf{x})$ represents the observed intensity at a pixel $\mathbf{x} = (x, y)$, $\mathbf{J}(\mathbf{x})$ is the original intensity reflected towards the observer from the corresponding scene point, $t(\mathbf{x})$ is the medium transmission which describes the portion of the light that is not scattered and not absorbed and reaches the camera, $\mathbf{A}$ represents the global atmospheric light which is a constant vector. In model (1), both $\mathbf{I}(\mathbf{x})$ and $\mathbf{J}(\mathbf{x})$ have three color channels, and only the input image $\mathbf{I}$ is known. With a single input image $\mathbf{I}$, we need to estimate the unknowns $\mathbf{J}$, t, and $\mathbf{A}$. We can see that image dehazing is essentially an ill-posed problem. Therefore, we need some assumptions or prior knowledge to solve this challenging problem.

According to the optical model (1), the observed intensity at the sensor is contributed by two components, the direct attenuation and airlight [11]. The first term $\mathbf{J}(\mathbf{x})t(\mathbf{x})$ on the right hand of model (1) is called direct attenuation, which describes the scene radiance's attenuation with increasing distance to the observer. The second component is called airlight, which is caused by the scattering of environmental illumination, including direct sunlight, diffuse skylight and light reflected by the ground, by particles suspended in the atmosphere [2]. Airlight is the primary cause of the color shifting, and its expression is $\mathbf{A}(1 - t(\mathbf{x}))$ in model (1).

In a homogeneous atmosphere, the transmission $t(\mathbf{x})$ can be expressed as

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

where β is the attenuation coefficient [3] due to scattering and absorption, and $d(\mathbf{x})$ represents the distance from the position of pixel $\mathbf{x}$ to the observer. Eq. (2) indicates that the contrast of the scene is reduced exponentially with the distance $d(\mathbf{x})$ increasing. The coefficient β is usually assumed constant in homogeneous medium [2].

2.2. Optical model in inhomogeneous atmosphere

As discussed in Section 2.1, the attenuation coefficient β is considered constant in homogeneous atmosphere. However, the atmospheric medium is not always uniform. Obviously in this situation, the assumption that the attenuation coefficient β is a constant is no longer suitable. In actual atmosphere, the distributions of aerosols are usually not uniform, or rather, they change significantly as a function of altitude. Since the attenuation coefficient β is a result of the scattering properties of the aerosols in the atmosphere, the significant variation in the density of aerosols leads to the change of the attenuation coefficient β [12].

The distributions of aerosols are dominated by gravity, and the density of aerosols presents the exponential decay with the height increasing

$$\rho(h(\mathbf{x})) = \rho_0 e^{-\alpha h(\mathbf{x})}. \tag{3}$$

Here, ρ is the aerosol concentration, ρ_0 is aerosol concentration at earth's surface, α is an exponential attenuation constant, and $h(\mathbf{x})$ represents the height from the pixel $\mathbf{x}$ to the observer.

Since the attenuation coefficient β is proportional to the density of aerosols, the attenuation coefficient also decreases exponentially with respect to height, which can be expressed as

$$\beta(h(\mathbf{x})) = \beta_0 e^{-\alpha h(\mathbf{x})}, \tag{4}$$

where β_0 is the value of attenuation coefficient at earth's surface. According to Eq. (4), the attenuation coefficient $\beta(h(\mathbf{x}))$ in inhomogeneous atmosphere becomes the constant attenuation coefficient β in homogeneous atmosphere when the exponential attenuation constant α is zero. Therefore, the attenuation coefficient model in homogeneous atmosphere is a special case of that in inhomogeneous atmosphere.

According to the definition of the attenuation coefficient in Eq. (4), the attenuation coefficient depends upon the height of objects in the inhomogeneous atmosphere, and a constant attenuation coefficient which is independent of the height is not accurate enough to describe the optical model. In addition, Eq. (4) gives a more accurate description of imaging process in actual atmosphere.

3. Single image dehazing in inhomogeneous atmosphere

This section investigates single image dehazing in inhomogeneous atmosphere. Our image dehazing work is based on the dark channel prior [9] and the guided filter [13]. The framework of our dehazing algorithm is shown in Fig. 1.