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A robust haze-removal scheme in polarimetric dehazing imaging based on automatic identification of sky region

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ABSTRACT

Quality enhancement of images acquired in hazy conditions is a significant research area in civil and military applications. The polarimetric dehazing methods have been exploited to dehaze hazy images and have proven to be effective in enhancing their quality. In this paper, by combining the polarimetric imaging technique and the dark channel prior technique, a robust haze-removal scheme is presented for the first time. On the one hand, the polarimetric imaging technique has advantages in recovering detailed information well, especially in dense hazy conditions; on the other hand, the dark channel prior technique provides a much more precise and convenient way to estimate the airlight radiance through extracting the sky region automatically. The experiments verify the practicability and effectiveness of the proposed dehazing scheme in quality enhancement of hazy images. Furthermore, comparison study demonstrates that the proposed scheme is superior to some sophisticated methods in terms of the visibility and contrast. We believe this scheme is beneficial in the image dehazing applications, especially for real-time applications.

1. Introduction

Images of outdoor scenes captured in hazy weather conditions are mainly degraded by the atmospheric absorption and scattering. The scene radiance is attenuated along the path of the light, and it is mixed with the atmospheric light scattered by haze particles, which is called the airlight [1–3]. These images usually show poor visibility and low contrast, which subsequently is an issue in many outdoor applications, such as remote sensing [4], accident investigation [5], etc. For this reason, researchers are focusing their attention on exploiting dehazing methods for enhancing the quality of hazy images.

A large number of methods have been developed for haze removal from images. These methods can be generally classified into two categories according to the number of images employed in dehazing process. One is based on the single-image haze-removal mechanism [6–13]; the other is based on the multi-image haze-removal mechanism [14–22]. For the first category, the quality of hazy images can be effectively improved with these methods, but they usually rely on some assumptions and/or prior knowledge since there are many unknown parameters which must be derived from the single input image. Originally these methods required significant computational time and lost some crucial information. Recently, due to the demand for real-time dehazing applications, many single image dehazing methods have been optimized and developed for real-time dehazing [10,12]. Within the second of the above-mentioned categories, polarimetric dehazing methods have been shown to be the most effective at enhancing the quality of hazy images [16–22]. Schechner et al. described the principle of the polarimetric dehazing method and demonstrated that this method can effectively enhance the quality of hazy images [16,17]. The airlight radiance can be estimated through two or more images with different polarization orientations, since it is invariably partially polarized [23]. This was followed by enhancements in image quality with very promising results [18,19]. Subsequently, Mudge *et al*. also published in this field but their methods are similar to Schechner's [20]. Meanwhile, these methods have been extended to underwater imaging applications [24,25]. Owing to the favorable results and high computational efficiency, the polarimetric dehazing methods are especially attractive.

In general, the airlight radiance (A) and the global atmospheric light radiance (A_∞) are two key parameters involved in the polarimetric dehazing methods. However, whereas several automatic ways of estimating A have been reported in single image haze removal techniques, until now the estimation of A and A_∞ could

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not be realized automatically during the process of polarimetric dehazing imaging. In this paper, with the inspiration of the dark channel prior technique, a new haze-removal scheme is proposed in which A and A_∞ can be estimated automatically. This is particularly important for the case of real-time polarimetric dehazing applications. Experimental results indicate that the dehazing capability of this scheme is significantly improved when compared with other reported dehazing methods. Comparison experiments not only prove the effectiveness of this scheme in enhancing the quality of hazy images, but also demonstrate its robustness.

2. Theoretical backgrounds

2.1. Polarimetric dehazing method

In computer vision, a widely used model for describing a hazy image is mathematically expressed by $I(x, y)=L(x, y)\cdot t(x, y)+A_\infty\cdot(1-t(x, y))$ [3]. In the polarimetric dehazing method, the above parameters have specific physical meaning. (x, y) is the pixel coordinate, I is the observed intensity by the camera, L is the scene radiance without being attenuated, t is the medium transmission and A_∞ is the global atmospheric light radiance. Note that t denotes the portion of light reaching the camera, and it can be represented as $t(x, y)=\exp[-\beta z(x, y)]$, where β is the extinction coefficient of the atmosphere with the assumption that it is distance-invariant. z is the distance between the scene and the camera. The term $L\cdot t$ is the direct transmission, indicating the scene radiance that reaches the camera. The airlight radiance, arising from the scattered light, can be expressed as $A=A_\infty\cdot(1-t)$. Combining these relations, L can be derived as [16]

$$L(x, y)=\frac{I(x, y)-A(x, y)}{1-A(x, y)/A_\infty}. \tag{1}$$

Eq. (1) shows that L can only be obtained if A and A_∞ are available. Furthermore the polarimetric dehazing effect directly depends on how accurate one can estimate A and A_∞. Hence, estimating A and A_∞ accurately becomes a key goal in the polarimetric dehazing method.

Mudge et al. described their method based on a polarimeter [20]. Four images are captured simultaneously, then $I^\perp$ and $I^\parallel$ are deduced according to Stokes parameters. Here $I^\perp$ is the image taken at the angle that has the most airlight and $I^\parallel$ corresponds to the image that has the least airlight [16]. In the sky region, there is no scene radiance, therefore $A=I$. Then the degree of polarization (DOP) of the airlight (p_A) can be obtained by

$$p_A=mean\left(\frac{A^\perp(x, y)-A^\parallel(x, y)}{A^\perp(x, y)+A^\parallel(x, y)}\right)=mean\left(\frac{I^\perp_{sky}(x, y)-I^\parallel_{sky}(x, y)}{I^\perp_{sky}(x, y)+I^\parallel_{sky}(x, y)}\right). \tag{2}$$

The airlight radiance of each pixel over the whole image can be estimated using $A(x, y)=(I^\perp(x, y)-I^\parallel(x, y))/p_A$. Meanwhile, A_∞ can be estimated from the brightest pixels in the sky region. Once A and A_∞ are known, the dehazed image can be obtained according to Eq. (1). However, the sky region needs to be marked out manually in their method [16,17].

2.2. The identification of sky region

The analysis for the polarimetric dehazing process always involves the estimation of the airlight radiance, especially the DOP of the airlight. Although the methods for estimation of DOP without the sky region in the images have been discussed in detail in [19], it is quite complicated. Considering the fact that the demands for dehazing techniques are generally in outdoor applications, in this case the acquired images always include a region (no matter how much the size is) which just corresponds to the sky region. In principle, those related parameters for dehazing can be obtained easily by just considering those pixels in the sky region. However, prior to the work presented in this paper there has been no reported method for extracting the sky region automatically.

In 2011, He et al. proposed a single-image dehazing method, namely the Dark Channel Prior method, which can achieve better dehazed images than previous methods [8]. In this method, the dark channel prior is utilized to estimate the medium transmission. The key idea of the dark channel prior is that in most of the skyless patches for haze-free images, at least one color channel has some pixels whose intensities are very low and close to zero. However, due to additional airlight, the dark channel image of a hazy image is brighter than its haze-free version. So the dark channel image of a hazy image roughly approximates the thickness of the haze [8]. What is important is that the brightest region of the dark channel image is exactly the sky region, which can be easily and automatically identified. This paper builds on the work from the dark channel prior method and applies it to the polarimetric dehazing method in order to effectively identifying the sky

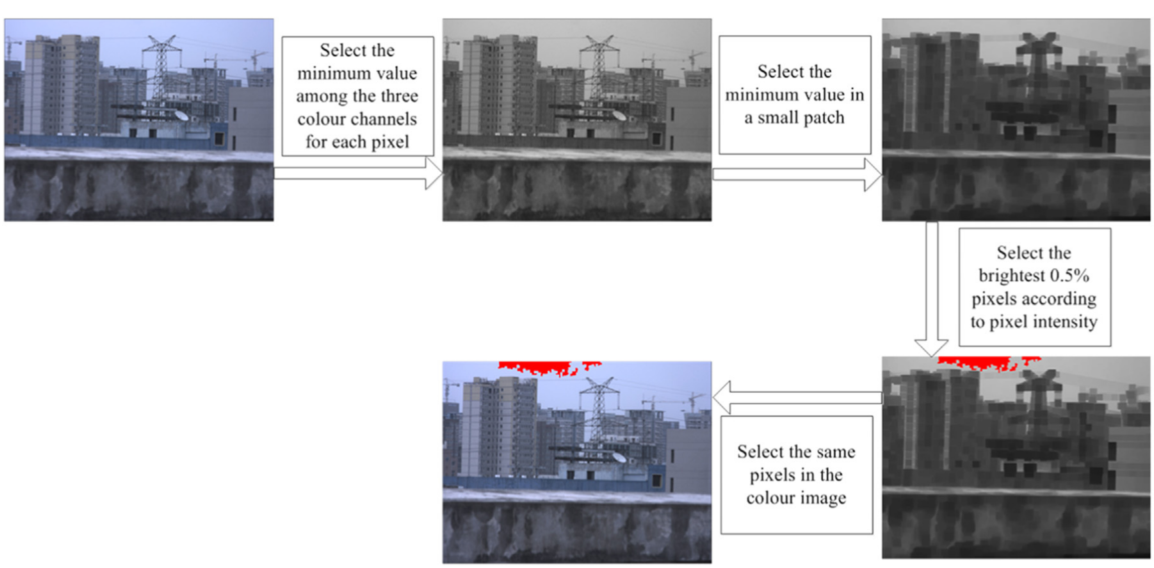

Fig. 1. The flowchart of the identification of the sky region.