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A novel dehazing model for remote sensing images☆

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ABSTRACT

The visibility of remote sensing images taken in poor environmental conditions is often degraded due to the occurrence of fog, haze, mist, and smog. To restore these images, many visibility restoration techniques have been developed. However, the existing techniques perform poorly to remove the effect of haze from remote sensing images with a complex background and large haze gradient. In this paper, a gradient profile prior is proposed to remove the haze from remote sensing images. The coarse estimated atmospheric veil has been refined by using gradient-based guided image filter. Moreover, the visibility restoration model has also been modified to overcome the over saturation and color distortion problems. Extensive experiments have shown that the proposed dehazing technique outperforms the existing image dehazing techniques. The proposed technique has significantly improved the spatial and radiometric information of remote sensing images.

1. Introduction

Due to a high spatial resolution of remote sensing images obtained from satellite-sensors have improved the opportunity of efficient earth observation [1]. These images are utilized in several applications such as Shadow detection, Land-cover change detection, Attitude jitter detection, Building extraction, Biophysical estimation, Temperature retrieval, Multi-specialist architecture, Target detection, etc[2]. Remote sensing images taken under hazy conditions suffer from poor visibility and low contrast problems [3]. The detailed information of hazy images is always lost. Therefore, these images limit their analysis for vision applications [4].

Haze is a regular environment occurrence in which elements obscure the clearness of environment. In the hazy environment, the captured remote sensing images have poor illumination. Therefore, dehazing techniques are required to remove/ reduce the effect of haze from the digital images. However, dehazing is a difficult task because the haze transmission (T_x) depends upon the unknown depth which fluctuates according to environment situations [5].

Several image enhancement techniques have been utilized to restore the hazy image such as histogram equalization [6], recursively separated and weighted histogram equalization [7], dynamic range separate histogram equalization [8], bi-histogram equalization [9], etc. However, histogram-based dehazing techniques suffer from saturated pixels, halo artifacts, gradient reversal artifacts, and edge preservation issues [10].

Physics-based dehazing techniques have the ability to overcome the issue of over-saturation [11]. However, [11] and [12] suffer from the halo artifacts and color distortion problems [13]. Dehazing techniques have made considerable improvements in recent times due to a utilization of efficient suppositions and priors. A dark channel prior technology is developed to handle this issue [12]. But, dark channel prior is worthless whenever the objects are intrinsically similar to airlight and no shadow is directed on them.

Shiau et al. [14] applied weighted technique and difference prior (WDP) to discover the probable atmospheric lights and lessen

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the halo artifact around gradients. Sun et al. [15] utilized atmospheric light estimation technique based on a physical model to remove the haze. It avoids adverse effects caused due to monitoring error of global atmospheric light. However, [14] and [15] based dehazing techniques suffer from color distortion problem.

Im et al. [16] combined color-channels transmission (CCT) map to evaluate low-contrast segments. The gradient coefficient is used to improve the contrast of under-exposed segments. Thus, it can preserve significant edges of a restored image. However, it suffers from gradient reversal and halo artifacts. Zhao et al. [17] used atmospheric transmission theory and weight analysis (ATW) to enhance the visibility of a degraded image. Weight analysis is used to produce better transmission map and determines the proper luminance of the sky. However, [16] and [17] based dehazing techniques are not suitable for images with large haze gradients. Also, these techniques may introduce gradient reversal artifacts.

Wang et al. [18] designed an atmosphere point spread function (APSF) using dark channel prior and multiple scattering. To minimize the halo artifact and color distortion, a superpixel technique is used to measure transmission map on the sky and non-sky region. Riaz et al. [19] implemented a guided fusion based dehazing (GFD) technique to overcome the drawbacks of dark channel prior based techniques. It provides a more natural restoration of hazy images, especially for sky regions. But, these dehazing techniques [18,19] are not so effective for images with large haze gradients. Dilbag and Kumar proved that the dark channel prior causes annoying halo and gradient reversal artifacts [20–22]. They used partial differential equations based filter (FPDE) to remove the haze from images in an efficient manner [23]. It minimizes various artifacts associated with existing haze removal techniques [5,20].

The main contribution of this paper is to develop an efficient gradient profile prior. It simultaneously restores the visibility of hazy image and removes artifacts. The restoration process of gradient profile prior is modified for detecting the brighter regions of hazy images. The gradient-based weighted guided image filter is developed to eliminate halo and gradient reversal artifacts. The gradient profile prior based dehazing technique is tested on five remote sensing images with respect to four performance metrics. The comparison of gradient profile prior is also done with seven competitive dehazing techniques.

The rest of paper has the following structure: Section 2 presents haze formation model. The proposed gradient profile prior is discussed in Section 3. In Section 4, the proposed approach is investigated on a set of images and compared with existing dehazing techniques. The concluding remarks are summarized in Section 5.

2. Haze formation model

The mathematical representation of hazy image is given as [2,22]:

$$F_{mg}(j) = A_{mg}(j)T_{mp}(j) + \mathscr{G}(1 - T_{mp}(j)) \tag{1}$$

Here, $F_{mg}(j)$ and $A_{mg}(j)$ denote hazy and actual images, respectively. $T_{mp}(j) \in [0, 1]$ is transmission map, $\mathscr{G}$ represents global atmospheric veil, and j demonstrates the coordinates of an image. The main focus of dehazing technique is to estimate $A_{mg}(j)$, $T_{mp}(j)$, and $\mathscr{G}$ from $F_{mg}(j)$.

$A_{mg}(j)T_{mp}(j)$ demonstrates direct attenuation. $\mathscr{G}(1 - T_{mp}(j))$ represents airlight map. Direct attenuation demonstrates the radiance of actual scene and decreases with respect to $T_{mp}(j)$. The airlight map increases whenever $T_{mp}(j)$ decreases. The primary reason behind this reduction is that actual image (A_{mg}) radiance is depleted by haze and far-away objects. In case of homogeneous hazy environment, $T_{mp}(j)$ can be represented as:

$$T_{mp}(j) = e^{-\gamma d(j)} \tag{2}$$

Here, γ is a medium extermination factor. $d(j)$ represents the depth of A_{mg}.

3. Proposed image dehazing technique

This section describes the mathematical formulation of proposed image dehazing technique. The proposed technique consists of five main stages. These are Gradient profile prior, Atmospheric veil estimation, Coarse atmospheric veil evaluation, Gradient-based weighted guided image filter, and Visibility restoration model. Fig. 1 shows the flow-diagram of proposed technique.

The brief description of these steps is given in preceding subsections.

3.1. Gradient profile prior

Sun et al. [24] designed an efficient gradient profile prior that implies the prior information of natural image gradients. In this prior, gradient profile represents 1-D profile of gradient magnitudes perpendicular to image structures. The gradient profile is modeled by a parametric gradient profile model. The image gradient (∇A_{mg}^{c}) is obtained by:

$$\nabla A_{mg}^{c} = (\partial_x, \partial_y) = m.\,\overrightarrow{N} \tag{3}$$

Here, c represents color channels, i.e., Red, Green, and Blue. The gradient magnitude (m) is computed as:

$$m = \sqrt{(\partial_x A_{mg}^{c})^2 + (\partial_y A_{mg}^{c})^2} \tag{4}$$

The gradient direction ($\overrightarrow{N}$) can be mathematically defined as: