Single Image Haze Removal with Pixel-based Transmission Map Estimation

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Abstract: Adversary imaging condition such as in a hazy weather is a challenge in the community of image processing. To address the challenge of haze removal, several model-based approaches have been reported recently. Among them, a single image haze removal scheme based on dark channel prior (DCP) was presented in [1] and has been getting popular because of its satisfactory performance for most of cases. However, it is well-known that the DCP scheme is inherent of two fundamental problems: high computational cost and over-exposure. In this paper, the objective of proposed dehazing algorithm (PDA) is to deal with the two problems in [1], where atmospheric light is estimated from the dark channel and pixel-based transmission map estimation is employed. Examples are given to verify the PDA where comparison with the DCP scheme and other well-known schemes are made as well. The simulation results indicate that the PDA has similar or better dehazing performance than the compared schemes in the given examples, when both mood retention and visibility improvement are considered.

Key-Words: haze removal, dark channel prior, halo, soft matting, transmission refinement, over-exposure

1 Introduction

As the cost of imaging sensors is getting lower and lower, imaging modules are embedded in many consumer electronic products, such as digital camera, mobile device, and smart phone. The key component in imaging modules is CMOS or CCD. In general, the CMOS and CCD work well in appropriate lighting condition and thus satisfactory images can be taken. However, the imaging performance of CMOS and CCD is limited at least in two aspects which are against the image quality. One is the low luminance and high contrast condition. The other is the adversary weather like a foggy or hazy condition. Traditionally, haze is an atmospheric phenomenon where particles obscure the clarity of the sky. To improve the visibility of hazy images, haze removal schemes are sought. Haze removal schemes can be roughly categorized as model-based or non-model-based where multiple-image or single image is used. In this paper, we concentrate ourselves on the model-based scheme with single image. Recently, several model-based schemes have been reported for single image haze removal. The challenge is to appropriately estimate the model parameters, such as atmospheric light and transmission map. In [3], the transmission and surface shading are assumed locally uncorrelated under which the albedo of the scene and the transmission are estimated. In [3], the performance of haze removal heavily depends on the assumption. That is, the dehazed result will be satisfied if the local uncorrelation assumption is appropriate, and vice versa. In [4], the dehazing problem was considered as a contrast enhancement problem. The motivation is based on the observation that an image with haze is of higher contrast than that in a hazy image. By the observation, an approach to maximize local contrast was proposed. However, the restored image may look unnatural because of local contrast maximization. In 2011, a popular single image dehazing scheme was proposed based on dark channel prior [1]. In [1], an interesting statistics is observed which is called dark channel prior (DCP). The prior is found by that some pixels are very often have very low values in at least one color channel, for a non-sky local region in outdoors haze-free images. The DCP-based scheme in [1] works well in general. However, the DCP dehazing scheme suffers from high computational cost and over-exposure. Many variations of the DCP scheme have been reported. In [2], an estimation of transmission map based on dual dark channels was proposed where soft matting is omitted. However, the halo problem is still remained. In [5], an optimization scheme was presented and a variation of minimum filter with shiftable window was proposed. Unfortunately, the halo problem is not solved. In [6], a prior called difference prior was reported with which a weighted scheme was used to estimate the transmission map. Though the visibility is improved, it suffers from color shift in dehazed images in general. In [7], a transmission map was refined based hidden Markov random field and expectation-maximization. It had shown that the dehazing performance is better than the DCP scheme. Nevertheless, it requires high computational cost. In [8], a linear color attenuation prior was proposed to estimate transmission map where a linear model and supervised learning is employed as well. Though the dehazed images of given examples show no color shift, it has to pay high computational cost.

In this paper, a dehazing algorithm with pixel-based transmission map estimation is presented where high computational cost and over-exposure problems are relieved. The organization of this paper is as follows: Section 2 briefly reviews the DCP scheme in [1]. In Section 3, an approach is presented to relieve the two problems in DCP scheme. In Section 4, two examples are provided to justify the proposed approach. Then conclusion is made in Section 5.

2 Review of the DCP scheme

Based on the dark channel prior (DCP), a dehazing algorithm is developed in [1] which is abbreviated as DCP scheme hereafter in this paper. In the DCP scheme, the following haze model is assumed:

$$I(x) = J(x) \cdot t(x) + A[1 - t(x)] \quad (1)$$

where $I(x)$ denotes the observed intensity, $J(x)$ the scene radiance, A the global atmospheric light, and $t(x)$ the transmission map. With the model in Eq. (1), given a color image I in RGB color space the implementation steps of DCP scheme, are summarized as follows:

Step 1. Calculate the dark channel through the minimum filter as

$$J^{dark}(x) = \min_{\Omega(x)}[\min_{c \in \{R,G,B\}}(I^c(y))] \quad (2)$$

where $I^c(y)$ is one of three components {R, G, B} in the input image and $\Omega(x)$ is a window centered at x.

Step 2. Estimate the transmission map as

$$\tilde{t}(x) = 1 - \omega \times J^{dark}(x) \quad (3)$$

where ω is a user-defined scaling factor.

Step 3. Obtain the refined $\tilde{t}(x)$, $t(x)$, by the soft matting.

Step 4. Estimate the global atmospheric light A by tracking back from 0.1% maxima of $J^{dark}(x)$ to the maximum of the corresponding pixels in the input image I.

Step 5. Recover the scene radiance as

$$\hat{J}(x) = \frac{I(x) - A}{\max[t(x), t_0]} + A \quad (4)$$

where t_0 is a user-defined lower bound of $t(x)$.

The flowchart of DCP scheme is shown in Figure 1. In general, the DCP scheme has satisfactory dehazing results. However, two problems are found in the DCP scheme. First, the soft matting is used to refine to avoid the halo problem. However, it results in the problem of high computational cost. Second, over-exposure may happen in dehazed images when very bright area is presented in the original image.

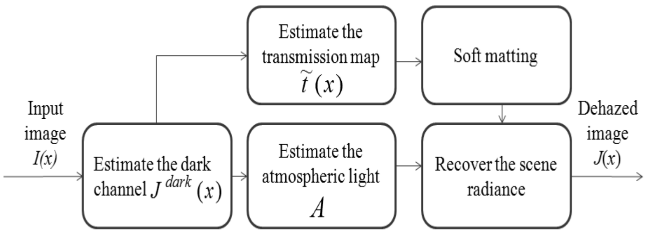


Figure 1. The flowchart of DCP scheme in [1]

3 The Proposed Approach

In this paper, two objectives are sought: (i) to reduce the computational cost in the DCP scheme by not using soft matting; (ii) to relief the over-exposure problem in the DCP scheme. The motivation and the proposed dehazing approach are given in Section 3.1 and Section 3.2, respectively.

3.1 Motivations

In this section, the motivations to relieve the two problems in the DCP scheme are described in the following.

3.1.1 Avoidance of soft matting and halos

Note that in the DCP scheme the dark channel is found by the minimum filtering with 15×15 window and that the transmission is obtained through the dark channel. The dark channel with 15×15 minimum filter make the objects mingled with part of image in the neighborhood, especially in the area of large depth discontinuities. Thus a serious halo problem arises if the transmission $t(x)$ is not refined. In the DCP scheme, the soft matting algorithm was used to refine $t(x)$ which results in the problem of high computation cost.

On the other hand, when observing transmission maps with different window sizes, we find a clue to avoid the soft matting. It is observed that no refinement is required at all and thus no halo problem either, if the 1×1 minimum filter is used to estimate the dark channel. In other words, the halo problem results from the dark channel found through minimum filter with 15×15 window. When 1×1 window is used, the transmission map needs no refinement. The problem now is how to compensate the dark channel estimated by 1×1 minimum filter. In this paper, an adaptive scaling factor is introduced to do the compensation. It is expected that the halo and high computational cost problems will be relieved at same time.

3.1.2 Solution to over-exposure problem

To deal with the over-exposure problem, it is observed that the way to estimate the atmospheric light *A* is not appropriate in [1]. Fortunately, we find that the atmospheric light *A* can be estimated directly by the dark channel estimated by 1×1 minimum filter, since they are correlated. Figure 2 is an example to show the relation between dark channel and the atmospheric light *A*. From Figure 2, one can see clearly the brightness of origin image is perfectly related to its dark channel. Consequently, the atmospheric light *A* can be estimated directly through the dark channel found by 1×1 minimum filter. In this paper, the atmospheric light *A* will be estimated by the maximum value in the dark channel with a scaling factor.

Figure 2. An example to show the relation of dark channel and atmospheric light *A*

3.2 The proposed dehazing algorithm

According to the motivations described in the previous section, the proposed dehazing algorithm (PDA) is given where (i) 1×1 minimum filter is used to estimate dark channel; (ii) the atmospheric light *A* is directly estimated from pixel-based dark channel; (iii) the soft matting to refine transmission map in [1] is avoided, and (iv) the final transmission map $t(x)$ is obtained through pixel-based dark channel after bilateral filtering. Given a hazy image *I* in RGB color space, the implementation steps of the PDA are described in the following:

Step 1. Calculate the dark channel

$$J_1^{dark}(x) = \min_{c\in\{R,G,B\}}[I^c(y))] \tag{5}$$

Step 2. Estimate atmospheric light *A* by $J_1^{dark}(x)$ as

$$A = \alpha \times \max_x[J_1^{dark}(x)] \tag{6}$$

where $0 < \alpha \le 1$ is a scaling factor.

Step 3. Calculate the standard deviation of J_1^{dark}, σ_J.

Step 4. Calculate the scaling factor *B*

$$B = \min(1.5*(1-\sigma_J), 0.8) \tag{7}$$

Step 5. Estimate the transmission map as

$$t(x) = 1 - B \times J_1^{dark} \tag{8}$$

Step 6. Apply the $W\times W$ bilateral filter to the transmission map $t(x)$.

Step 7. Recover the scene radiance as

$$J(x) = \frac{I(x) - A}{\max[t(x), t_0]} + A \tag{9}$$

where t_0 is a user-defined lower bound of $t(x)$.

The flowchart of the PDA is depicted in Figure 3. Two points should be noted. First, the transmission map $t(x)$ is estimated from the pixel-based dark channel $J_1^{dark}(x)$. Thus, $t(x)$ is a pixel-based estimation and no refinement is required accordingly. Second, the computational cost is relieved since the soft matting has been avoided and a bilateral filter is employed to refine the transmission, when compared with the DCP scheme.

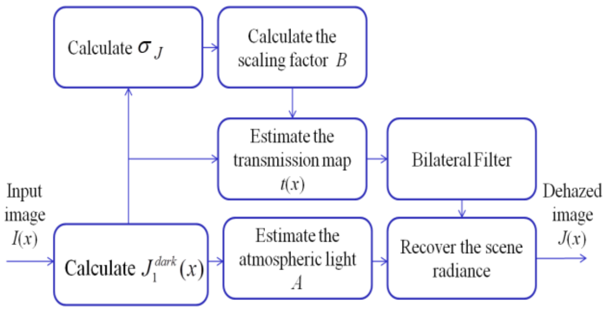


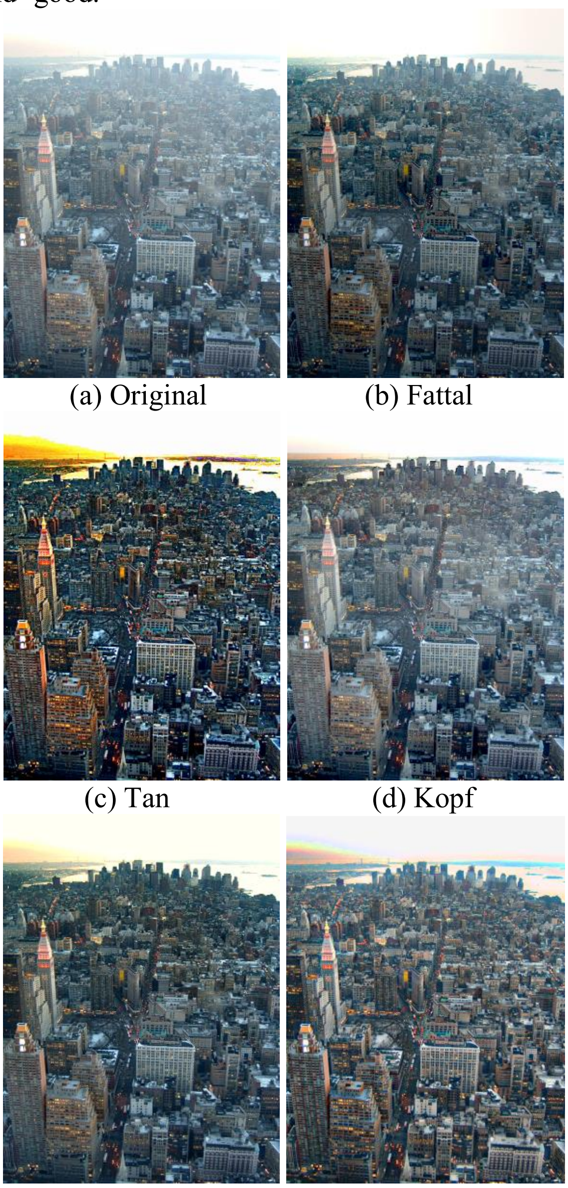
Figure 3. The flowchart of PDA

4 Simulation Results

In this section, two images are provided to verify the PDA: ny12 and y16 which are shown in Figure 4(a) and Figure 5(a), respectively. Besides, comparisons with the schemes proposed by Fattal, Tan, Kopf, He and Tarel are made as well where He scheme is the DCP scheme. The dehazed images of the compared schemes come from the website [9]. For details, one may visit the website. In the PDA, the parameters $\alpha = 0.9$ and $t_0 = 0.1$ while the window size $W\times W$= 9×9 is employed in the bilateral filter.

For the given examples, two subjective aspects will be considered in the comparison. One is the mood retention which concerns the color shift between the original image and its dehazed image. The other is the dehazing performance which emphasizes on visibility improvement.

As the first example, image ny12 and its dehazed images are shown in Figure 4. A subjective comparison of mood retention is given in Table 1 where the results are classified as ‘poor,’ ‘moderate,’ and ‘good.’



(a) Original (b) Fattal

(c) Tan (d) Kopf

(e) He (f) Tarel

(g) The PDA

Figure 4. Original ny12 and its dehazed images

Table 1. A subjective comparison of mood retention (image ny12)

scheme	poor	moderate	good
Fattal			•
Tan	•		
Kopf			•
He		•	
Tarel		•	
PDA			•

Table 2 indicates a subjective comparison of visibility improvement where three classifications are used as in Table 1.

Table 2. A subjective comparison of visibility improvement (image ny12)

scheme	poor	moderate	good
Fattal		•	
Tan			•
Kopf	•		
He		•	
Tarel			•
PDA		•	

By the results shown in Tables 1 and 2, an interesting observation is that it seems not able to have both good mood retention and good visibility improvement for the dehazing schemes. For example, Tan’s scheme has good visibility improvement but poor mood retention. And Kopf’s scheme is of good mood retention but poor visibility improvement. When both results in Tables 1 and 2 are considered, it seems reasonable to say the PDA and Fattal’s scheme outperform the other schemes. In the given example, the PDA and Fattal’s scheme have similar performances, even the PDA needs less computational cost.

The second example is image y16 which is shown in Figure 5(a) and its dehazed images are shown in Figures 5(b) to 5(g), respectively. As in the first example, a subjective comparison of mood distortion is given in Table 3.


(a) Original (b) Fattal


(c) Tan (d) Kopf


(e) He (f) Tarel

(g) The PDA

Figure 5. Original y16 and its dehazed images

Table 3. A subjective comparison of mood retention (image y16)

scheme	poor	moderate	good
Fattal		•	
Tan	•		
Kopf			•
He		•	
Tarel		•	
PDA			•

Table 4 indicates a subjective comparison of visibility improvement for the example y16.

Table 4. A subjective comparison of visibility improvement (image y16)

scheme	poor	moderate	good
Fattal	•		
Tan			•
Kopf	•		
He			•
Tarel			•
PDA			•

By the results shown in Tables 3 and 4, similar observation related to mood retention and visibility improvement in the compared schemes can be found in this example. Tan's scheme has good visibility improvement but poor mood retention where some artefact of contours are found in Figure 5(c). And Fattal's scheme is of good mood retention but poor visibility improvement. When both results in Tables 3 and 4 are considered, it is convinced to say the PDA has better performance than the other schemes. The given two examples have justified that the PDA generally has similar or better performance than the compared schemes when both mood retention and visibility improvement are considered.

5 Conclusion

This paper has presented a single image dehazing algorithm where transmission map was estimated by pixel-based dark channel. When compared with the DCP scheme, the soft matting was not used, instead a bilateral filter was used to refine transmission map. Accordingly, the problem of high computational cost is relieved. Two examples were provided to justify the proposed dehazing algorithm where comparison was made with other known dehazing schemes. Simulation results showed that the proposed dehazing algorithm has similar or better performance to the compared schemes, when both mood retention and visibility improvement are considered.

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