

Single Image Dehazing Based on Pixel Minimum Channel

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Abstract—Single image dehazing is an active research area in the image processing field. A popular model-based scheme based on the dark channel prior (DCP) prevails in single image dehazing because of its satisfactory performance for most of cases. However, it is well-known that the DCP scheme suffers from high computational cost to refine the transmission map. It is observed that the problem in the DCP scheme because of the block-based dark channel estimation. In this paper, we present a single image dehazing scheme based on pixel minimum channel (PMC) to relieve the problem of high computational cost. The simulation results indicate that the proposed PMC based scheme outperforms the compared schemes when both efficiency and visual quality are considered.

Keywords: haze removal; dark channel prior; pixel minimum channel; guided image filter

I. INTRODUCTION

Nowadays, imaging sensors, CCD or CMOS, are much cheaper than before and thus many consumer electronic products are equipped a CCD or CMOS sensor as a fundamental component. Though the imaging sensor generally works well in most of cases, however its visual quality is limited by the adversary weather like a hazy condition. Consequently, image enhancement or image restoration is sought to remove the effect of hazy weather. This kind of scheme is called image haze removal or image dehazing scheme. Physically, haze is an atmospheric phenomenon where particles degrade the visibility of scenes in images. To improve the visibility of hazy images, many image dehazing schemes have been proposed up to present. Those schemes can be roughly categorized as model-based or non-model-based schemes where multiple-image or single image are used. In this paper, we concentrate ourselves on the model-based scheme with single image. The challenge for the model-based schemes is to appropriately estimate the model parameters, i.e., the atmospheric light and the transmission map. Some model-based schemes for single image haze removal are given as follows. In [3], the transmission and surface shading are assumed locally uncorrelated under which the albedo of the scene and the transmission are estimated. However, the dehazing performance heavily depends on the assumption. In other words, the dehazed result will be satisfied if the local uncorrelation assumption is appropriate, and vice versa. In [4], the viewpoint of contrast enhancement is employed to deal with the dehazing problem. The fundamental idea is that an image without haze is of higher contrast than that in a hazy image. Thus, a dehazed

image is obtained by maximizing the contrast locally. However, the restored image may look unnatural in general. In 2009, a single image dehazing scheme was proposed based on dark channel prior (DCP) [1], which is observed in hazy images. The DCP suggests that some pixels are usually have very low pixel values in at least one color channel, for a non-sky local region in outdoors haze-free images. Since the DCP tackles the equation of hazy image model much easier than other previous schemes, it prevails in the field of image haze removal. In spite of the DCP scheme in [1] works well generally, it, however, suffers from the problem high computational cost which comes from the transmission refinement with the soft matting algorithm. This problem hinders the application of the DCP scheme to high resolution images. To deal with the problem, many variations of the DCP scheme have been reported. In [2], an estimation of transmission map based on dual dark channels was proposed where the soft matting algorithm is omitted. However, a minor 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 on 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 with supervised learning is employed. Though the dehazed images are satisfactory, it has to pay high computational cost. To sum up, the reported dehazing schemes suffer from the problem in either high computation cost or poor dehazing performance in some cases. In this paper, a single image dehazing scheme based on pixel minimum channel (PMC) is presented. The proposed PMC scheme attempts to relieve the problem of high computational cost and to handle high resolution images. The organization of this paper is as follows: Section II briefly reviews the DCP scheme in [1]. In Section III, the proposed PMC dehazing scheme is introduced where the motivation is given as well. In Section IV, several examples are provided to justify the proposed PMC scheme. Then conclusion and further research are given in Section V.

II. REVIEW OF THE DCP SCHEME

For the model based dehazing schemes, the following hazy image model is generally 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. According to the model in (1), the DCP scheme is developed in [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 a block-based 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 $\{R, G, B\}$ components in the input image I 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 $t(x)$.

In general, the DCP scheme has satisfactory dehazing results. However, an inherent problem is found in the DCP scheme, that is, the soft matting is used to refine the transmission map in order to avoid the halo problem. This hinders the application to high resolution images.

III. THE PROPOSED PMC SCHEME

In this paper, a single image dehazing scheme based on pixel minimum channel (PMC) is proposed where the model in (1) is assumed. The model parameters A and $t(x)$ will be estimated through the PMC. By this doing, the efficiency of the proposed dehazing scheme is expected. The motivation for the PMC scheme is described in Section III.A and its implementation steps are given in Section III.B.

A. Motivation

In this section, the motivation of the proposed PMC scheme is given in the following. Based on the PMC, the way to estimate the atmospheric light is described first and then the transmission map.

Atmospheric light estimated by the PMC

In the PMC scheme, the atmospheric light A can be estimated directly by the PMC, which comes from the 1×1 minimum filtering. In most of dehazing schemes, the atmospheric light is estimated through the brightest pixel in images. Figure 1 is an example to show the relation between the PMC and the atmospheric light A . From Figure 1, one can see clearly the brightness of origin image is perfectly related to its PMC. Consequently, the atmospheric light A will be estimated directly through the maximum value of PMC with a scaling factor.



(a) Image Sweden

(b) the PMC of Sweden

Figure 1. An example to show the relation of the PMC and the atmospheric light A

Transmission map estimated by the PMC and guided image filtering

It is observed that in the DCP scheme the way to find the transmission map involves two stages: First, obtain the dark channel by the minimum filtering with 15×15 window and the initial transmission map is found through inverting the block-based 15×15 dark channel. Second, refine the initial transmission map by the soft matting algorithm which requires a high computational cost. In the proposed PMC scheme, the transmission map are obtained by the following stages: First, find the initial transmission map as the PMC which is found by 1×1 minimum filter. Second, use the guided image filter [9] to refine the initial transmission map. The way to estimate the transmission map in the proposed PMC scheme is more efficient than the DCP scheme because the guided filter is more efficient than the soft matting algorithm. An example to show the difference of transmission maps between the proposed PMC scheme and the DCP scheme is given in Figure 2. In Figure 2, one may see that the edges of objects is more confined for the proposed PMC scheme while the DCP scheme mingles the background and foreground of objects even after the soft matting algorithm. The effectiveness of the proposed way to estimate the transmission map will be verified and compared with the DCP scheme later in Section IV.



(a) He scheme

(b) PMC scheme

Figure 2. An example to show the difference of final transmission maps obtained by the PMC and the DCP scheme

B. The proposed PMC dehazing scheme

According to the motivation described in the previous section, here the proposed PMC scheme is introduced where (i) 1×1 minimum filter is used to find the pixel minimum channel (PMC); (ii) the atmospheric light A is directly estimated from the PMC; (iii) the initial transmission map is obtained from the PMC, and (iv) the final transmission map $t(x)$ is through the guided image filtering on the initial transmission map. Given a hazy image I in RGB color space, the implementation steps of the proposed PMC scheme are described in the following:

Step 1. Calculate the pixel minimum channel as

$$I_{pmc}(x) = \min_{c \in \{R, G, B\}} [I^c(y)] \quad (5)$$

Step 2. Estimate atmospheric light A by $I_{pmc}(x)$ as

$$A = \alpha \times \max_x [I_{pmc}(x)] \quad (6)$$

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

Step 3. Calculate the standard deviation of I_{pmc} , σ .

Step 4. Calculate the scaling factor B

$$B = \min(1.5 \times (1 - \sigma), 0.75) \quad (7)$$

Step 5. Estimate the initial transmission map as

$$t(x) = 1 - B \times I_{pmc} \quad (8)$$

Step 6. Apply the guided image filter to refine the initial transmission map $t(x)$.

Step 7. Recover the scene radiance as

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

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

The flowchart of the proposed PMC scheme is depicted in Figure 3. There at least two points should be noted in the proposed PMC scheme. First, the initial transmission map $t(x)$ is estimated by the PMC, $I_{pmc}(x)$ and refined by the guided image filtering. This means a more efficient way for a more confined transmission map. Second, the computational cost is low since the PMC is used to find the atmospheric light and the transmission map with an efficient guided image filter. To sum up, the proposed PMC scheme is an efficient approach to single image dehazing. This will be verified in Section IV.

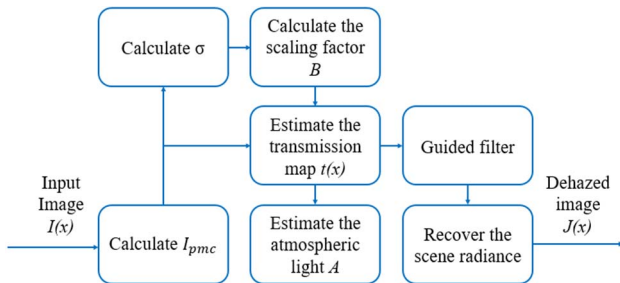


Figure 3. The flowchart of the proposed PMC scheme

IV. SIMULATION RESULTS

In this section, four images are provided to justify the proposed PMC scheme. These images are Girl (513×768), Forest (425×600), Sweden (400×600), and a high resolution image Mountain with image size 3,240×4,320.

In the simulation, the parameters of the proposed PMC scheme are set as $\alpha = 0.95$ and $t_0 = 0.1$. The program is coded with MATLAB R2015b and run under Windows 7 in a virtual machine in MacBook Pro with CPU 2.9 GHz Intel Core i5 and memory 16 GB, 1867 MHz, DDR3. Besides, comparisons with the schemes proposed by He in [1] and Tarel in [10] are made as well where He scheme is the DCP scheme.

As the first example, the original image Girl, its $I_{pmc}(x)$, the refined transmission map $t(x)$, and the corresponding dehazed image $J(x)$ are shown in Figure 4. The dehazed images from He's and Tarel's schemes are also given in Figure 4. For the visual quality of dehazed images, the PMC scheme is superior to the Tarel's scheme and has similar result to the He's scheme.

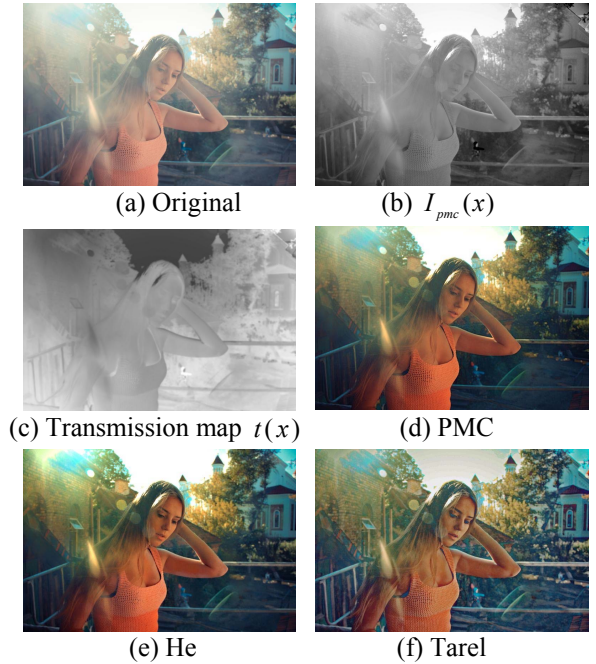


Figure 4. Image girl and its corresponding result

As for the efficiency, Table 1 shows the runtime of each dehazing schemes. It indicates that the proposed PMC scheme is 19.58 times faster than the He scheme and 8.38 times faster than the Tarel scheme, respectively.

Table 1. Comparison of runtime (image Girl)

scheme	runtime (second)
He	30.74
Tarel	13.16
PMC	1.57

The second example is image Forest which is shown in Figure 5(a) and its $I_{pmc}(x)$, transmission map $t(x)$, and the dehazed image $J(x)$ are shown in Figures 5(b) to 5(d), respectively. The results from He's and Tarel's schemes are also given in Figure 5(e) and 5(f), respectively. By Figure 5, the PMC scheme has similar result to the He's scheme and the Tarel's scheme has better visual quality among the compared schemes.

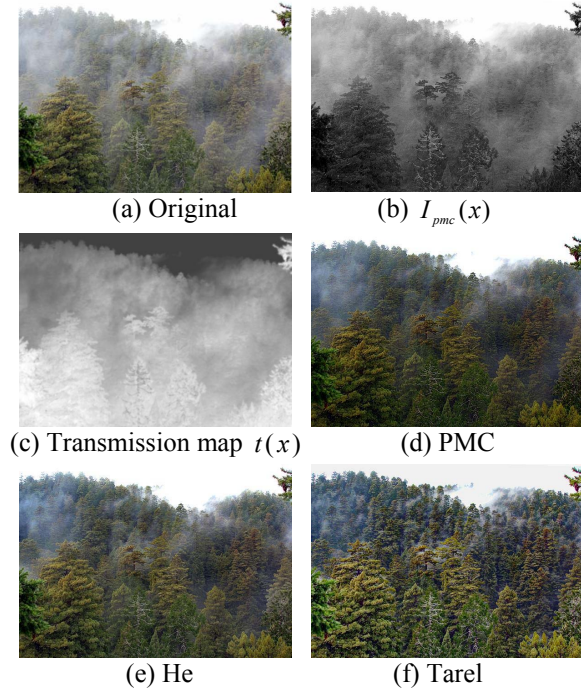


Figure 5. Image forest and its corresponding results

As for the runtime, the PMC scheme is 14.64 times faster than the He's scheme and 5.59 times faster than the Tarel's scheme. The runtime comparison is recorded in Table 2.

Table 2. Comparison of runtime (image Forest)

scheme	runtime (second)
He	19.768970
Tarel	7.539465
PMC	1.349288

In third example, the original image Sweden, its $I_{pmc}(x)$, the final transmission map $t(x)$, and the dehazed image $J(x)$ are given in Figure 6 where the dehazed images obtained from the He's and Tarel's schemes are shown as well for comparison. In this example, the PMC scheme has best visual quality. Some artefact can be found around the car in the result for the He's scheme while minor artefacts and poor dehazing performance are found in the Tarel's scheme.

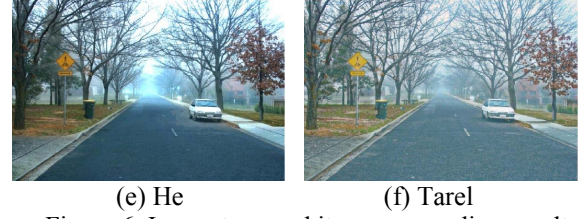
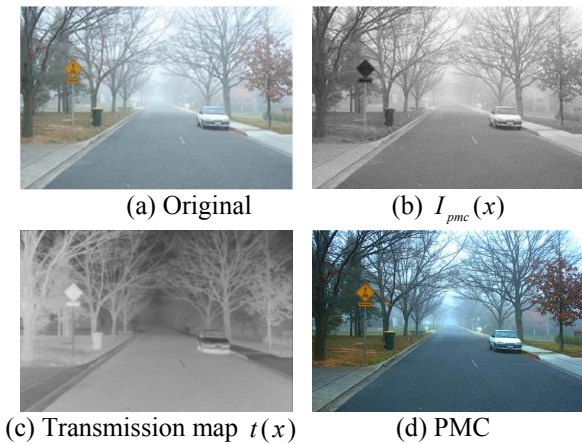


Figure 6. Image toys and its corresponding results

The runtimes for each scheme are given in Table 3. In the given example, the PMC scheme is 14.56 times faster than the He's scheme and 5.41 times faster than the Tarel's scheme, respectively.

Table 3. Comparison of runtime (image Sweden)

scheme	runtime (second)
He	13.546919
Tarel	3.718544
PMC	1.173997

The last example, image Mountain, is intended to show the proposed PMC scheme is able to handle high resolution images which are getting more popular in many imaging devices. The image size is as high as $3,240 \times 4,320$. It takes 14.98 seconds to obtain the dehazed image. However, the He and Tarel schemes have a difficulty to handle this case. It has been tried to get the results. Unfortunately, it takes a very long time to run the available algorithms but end up without any result. Consequently, no dehazed image for the He's and Tarel's schemes can be provided in Figure 7.

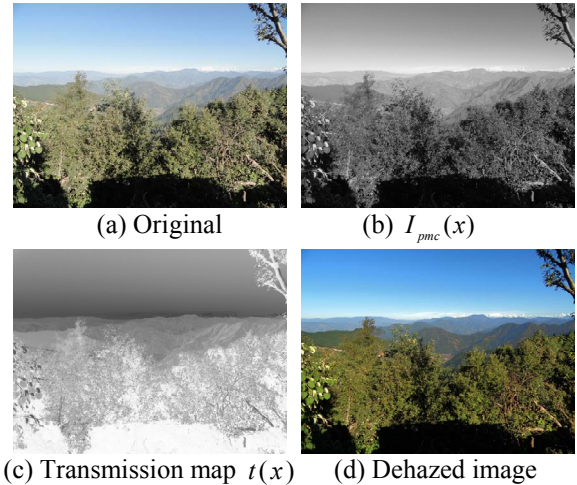


Figure 7. Image Mountain and its corresponding result

V. CONCLUSION

This paper has presented a single image dehazing algorithm where transmission map was estimated by pixel minimum channel (PMC). In the proposed PMC scheme, the guided image filter is used to refine the initial transmission map. Since the calculation of PMC is simple and the guided image filter is efficient, thus the proposed PMC scheme is more efficient than the compared schemes. Several examples has provided to show the dehazing effectiveness of the proposed PMC scheme. The simulation results indicate that the PMC scheme has similar or better visual quality. In the given examples, a high resolution is used to show that the proposed PMC

scheme is able to take care of the example efficiently and effectively while the He's and Tarel's schemes have a hard time, if not applicable, to deal with this example. In the further research, a way to enhance the visual quality of dehazed images will be sought.

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