Image Dehazing Using Dark Channel Prior and Fast Guided Filter in Daubechies Lifting Wavelet Transform Domain

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***Abstract*—**In this paper a novel method for image dehazing is proposed in lifting wavelet transform domain. Lifting Daubechies (D4) wavelet has been used to obtain the approximate image and detail images. As the haze is contained in low frequency part, only the approximate image is used for further processing. This region is processed by dehazing algorithm based on dark channel prior (DCP). The dehazed approximate image is then recombined with the detail images using inverse lifting wavelet transform. Implementation of lifting wavelet transform has the advantage of auxiliary memory saving, fast implementation and simplicity. Also, the proposed method deals with near white scene problem, blue horizon issue and localized light sources in a way to enhance image quality and makes the algorithm robust. Simulation results present improvement in terms of visual quality, parameters such as root mean square (RMS) contrast, structural similarity index (SSIM), entropy and execution time.

***Keywords*—**Dark channel prior, image dehazing, lifting wavelet transform.

I. Introduction

HAZE removal is a critical need of many computer vision applications, where high visual quality of images is required. But doing this is not easy as haze thickness depends on an unknown parameter ‘depth’. This makes single image haze removal a highly under constrained problem. To solve this, an assumption or prior is needed. More the correctness of the prior, better the quality and fidelity of the haze free image.

In recent times, single image haze removal based on DCP proposed by He et al. [1], [2] has been widely used for image dehazing purpose. In most of the outdoor clear images, there exists at least one color in RGB color space that is nearly zero in a window. Various techniques have been proposed in literature to improve and optimize the algorithm for different imaging conditions. In this paper, DCP together with fast guiding filter has been used in lifting wavelet transform domain to improve the image quality. To deal with the issue of blue horizon in traditional DCP and to preserve the natural colors of the image, transmission has been computed for each color channel separately [3]. At last, transmission correction factor and hybrid adaptive patch size has been applied to solve the near white scene problem and issue of localized light sources respectively.

II. Background

A. Haze Imaging Model

The hazy image equation generally utilized as a part of dehazing procedure is:

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

where, x is location of the pixel, I is input hazy image, J is haze free image, A is airlight and t is transmission of the medium through which light travels, i.e., air in present case.

The first term $t(x)J(x)$ is direct attenuation, that is, amount of light reaching the camera straight from the object with multiplication of the attenuation factor caused by the medium.

The second term $A(1 - t(x))$ is airlight that adds in the radiance as the indirect scattered light enters the camera because of the presence of haze in the air.

B. Literature Survey

Variations of DCP algorithm has been used in literature for image dehazing. To reduce the blocky artifacts and thus to increase the accuracy of transmission estimation, authors in [4] calculated the dark channel after segmenting the hazy image into super pixels. However, transmission refinement was still required to combat the remaining artifacts. Their approach preserves the edges but, the results depend on number of super pixels and amount of haze contained in the image. Bo-Hao Chen et al [5] stated in their study that entropy of gradient magnitude of hazy image is indicator of haze thickness. They used this entropy to correct the transmission in DCP algorithm.

Some techniques focus on time-consuming refinement process to save computation cost. C.H. Hsieh et al. [6] proposed pixel based dark channel, i.e., patch of size 1x1, eliminating the need of soft matting. The method works fast, but, it has the disadvantage of halo artifacts. Yogesh et al. [3] deployed erosion and dilation for refinement process. The method is confined to a patch size of (3x3) beyond which it is not able to eliminate halos. Also, the moment it achieves halo removal, oversaturation of image emerges as a new problem. H.Yu Yang

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et al. [7] used median filter to refine the transmission inherently in the algorithm. Y. Yang et al. [8] used discrete Haar wavelet transform and guided filtering [9] to speed up the dehazing algorithm. Y. Song et al. [10] used pixel wise dark channel or local maximum saturation as guiding image for guided filter refinement. This enhanced the speed of the algorithm as guiding images are grey scaled in contrast to RGB.

Dark channel assumption of He [1] fails in sky regions and in presence of light sources. This leads to inaccurate transmission estimation and oversaturation. In [11], authors calculated the brightness map which is then utilized to raise the accuracy of transmission estimated by DCP algorithm. For accurate air light estimation, C.H. Yeh et al. [12] introduced an additional bright channel prior to detect regions with minimal haze density. The criterion fails for black objects and shadow regions. Jiajie Liu et al. [13] optimized transmission by utilizing the difference of image intensity and air light for every pixel. It performs satisfactorily in sky region however, performance degrades for non-sky images. Yi-Jui Cheng et al. [14] resolved the localized light sources impact by computing the air light from dark channel of 45×45 patch size. C. Chengtao et al. [15] segmented the image into two regions: sky and non-sky and determined their parameters independent of each other. The method, however, does not appear to be very friendly, as it requires image dependent threshold value for segmentation purpose. T. Han and Y. Wan [16] proposed method for accurate transmission parameter estimation. The value of estimated transmission is varied according to the distance of pixel intensity from air light. The method works well for sky parts but, leads to oversaturation in other parts of the image. Xipan Lu et al. [17] solved this problem by using a compensation term in transmission computation that considers sky region.

Another case of over saturation occurs when white objects are present in near scenes of the image. In this case also, dark channel is not dark leading to underestimation of transmission. He et al. [1] stated this as ‘white marble problem’. C. Yang and F. Liu [18] resolved the near white object problem inspired by underwater dehazing [19]. They increased the transmission with an additive term based on the deviation of difference of maximum and minimum pixel color channel intensity from the average.

C. Conventional Dark Channel Prior Based Approach

The conventional dehazing approach based on DCP involves following steps:

1. Dark Channel Computation

Dark channel is calculated with two minimum operations as:

$$I^{dark}(x) = \min_{y\in\Omega(x)}\left(\min_{c\in\{R,G,B\}} I^c(y)\right) \tag{2}$$

where, c refers to the color channel in the RGB color space and Ω refers to the window considered for dark channel computation.

2. Air Light Estimation

To estimate air light, average intensity of pixels in hazy image corresponding to 0.1% of the pixels in the dark channel having highest intensity values has been calculated for each color channel.

3. Transmission Estimation

The transmission is calculated from (1) as:

$$\tilde{t}(x) = 1 - \min_{y\in\Omega(x)}\left(\min_{c}\frac{I^c(x)}{A^c}\right) \tag{3}$$

4. Transmission Refinement Using Guided Filter

To reduce the execution time overhead caused by soft matting refinement [20], He [1] developed and used edge aware filtering technique -‘Guided Filter’ [9]. This led to significant increase in speed of the dehazing algorithm.

III. Proposed Method

In the proposed algorithm, following shortcomings of He’s method has been attempted to overcome:

1. High computation time.
2. Incorrect estimation of air light in presence of localized light sources.
3. Saturation of near white objects.
4. Bluishness of scenes near horizon.

At first, hazy image is decomposed using D4 lifting wavelet transform into approximate and detail images. Then, the atmospheric light is estimated as the average of the 0.1% of the brightest pixels in the dark channel for each color channel, which is followed by transmission estimation.

Transmission is estimated separately for each color channel for blue horizon issue. To deal with near white scene problem, transmission is corrected using adaptive pixel based correction factor. The blocky artifacts obtained in the transmission have been removed using fast guided filter. By substituting estimated transmission and air light in the hazy image equation, haze free low frequency component of the input image is obtained. At last, this dehazed approximate image is combined together with detail images using inverse lifting wavelet transform to obtain the final haze free output image. The proposed algorithm is shown in Fig. 5. It involves following steps:

A. Step Up Using Wavelet Decomposition

Since haze is a low frequency phenomenon, in the proposed method, only the low frequency part of the picture is processed instead of processing the entire image. This gives classical DCP algorithm ample speed boost.

Y. Yang et al. [8] decomposed hazy image into four components-image approximation, vertical details, horizontal details and diagonal details using Haar discrete wavelet transform.

In the proposed method, D4 has been used for the wavelet part to obtain approximation image. It has been implemented using lifting scheme, developed by Wim Sweldens [21]-[24].

The advantages of Lifting scheme are numerous:

1. It does not involve complex operations of convolution, up-sampling and down-sampling.
2. To implement any discrete wavelet transform, only finite number of lifting steps are needed.

3. It is faster as compared to standard wavelet implementation.
4. Due to in place implementation, lifting wavelet transform requires less memory.
5. Any lifting transform is immediately reversible, simply by changing + with – and vice versa

Lifting involves three steps:

1. Split: This step divides input signal f into even and odd polyphase components:

$$\begin{array}{c} Even\ component: f(2n); \\ odd\ component: f(2n+1) \end{array} \quad (4)$$

2. Predict (dual lifting): This step predicts odd components from neighboring even components with predictor operation P and details d as prediction error:

$$d(n) = f(2n+1) - P(f(2n)) \quad (5)$$

Odd components are then retrieved as:

$$f(2n+1) = P(x(2n)) + d(n) \quad (6)$$

3. Update (primal lifting): This step updates the even samples with an update operator U applied to detail sequence to produce approximate wavelet components s.

$$s(n) = f(2n) + U(d(n)) = (f(2n) + f(2n+1))/2 \quad (7)$$

D4 lifting wavelet consists of following steps: forward D4 wavelet transform:

Split $$\lambda_{-1,k} = f(2k)\ and\ \gamma_{-1,k} = f(2k+1) \quad (8)$$

Update 1 $$\lambda_{-1,k} = \lambda_{-1,k} + \sqrt{3}\,\gamma_{-1,k} \quad (9)$$

Predict $$\gamma_{-1,k} = \gamma_{-1,k} - \frac{\sqrt{3}}{4}\lambda_{-1,k} - \frac{\sqrt{3}-2}{4}\lambda_{-1,k-1} \quad (10)$$

Update 2 $$\lambda_{-1,k} = \lambda_{-1,k} - \gamma_{-1,k+1} \quad (11)$$

Normalize $$\lambda_{-1,k} = \frac{\sqrt{3}-1}{\sqrt{2}}\lambda_{-1,k}\ and\ \gamma_{-1,k} = \frac{\sqrt{3}+1}{\sqrt{2}}\gamma_{-1,k} \quad (12)$$

Inverse D4 wavelet transform consists of following steps:

$$\lambda_{-1,k} = \frac{\sqrt{3}+1}{\sqrt{2}}\lambda_{-1,k}\ and\ \gamma_{-1,k} = \frac{\sqrt{3}-1}{\sqrt{2}}\gamma_{-1,k} \quad (13)$$

$$\lambda_{-1,k} = \lambda_{-1,k} + \gamma_{-1,k+1} \quad (14)$$

$$\gamma_{-1,k} = \gamma_{-1,k} + \frac{\sqrt{3}}{4}\lambda_{-1,k} + \frac{\sqrt{3}-2}{4}\lambda_{-1,k-1} \quad (15)$$

$$\lambda_{-1,k} = \lambda_{-1,k} - \sqrt{3}\,\gamma_{-1,k} \quad (16)$$

where λ and γ are the approximate and detail coefficients respectively. Figs. 1 and 2 show the hazy image and its corresponding wavelet decomposition components using lifting D4 wavelet.

B. Determining the Patch Size

The probability of obtaining a pixel from RGB color space decreases with use of small patch size. In such case, transmission computation (3) becomes less accurate. For large patch sizes, transmission computation is more accurate. However, opting for larger patch size leads to stronger halo and blocky artifact. It is still possible to deal with these artifacts with the help of various refinement techniques. Fig. 3 illustrates the impact of various patch sizes. Fig. 3 shows that when patch size is larger than required, some haze is left in the image.

Fig. 1 Input hazy image

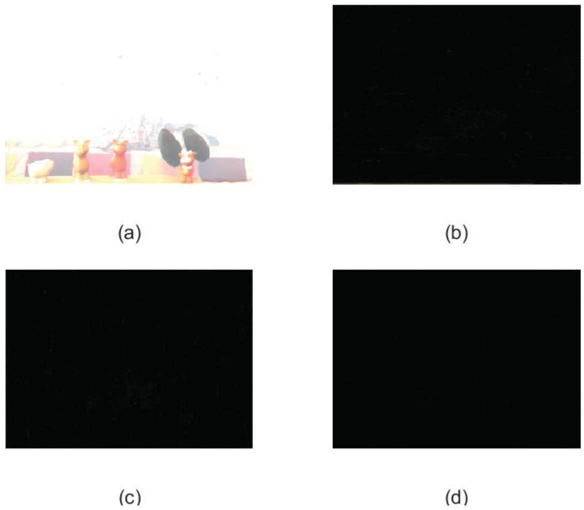

Fig. 2 Wavelet components (a) CA: Approximation (b) CH: Horizontal (c) CV: Vertical (d) CD: Diagonal

Fig. 3 Recovering images using different patch sizes (a) Input hazy images (b) Using 3 × 3 patches (c) Using 15 × 15 patches (d) Using 30 × 30 patches [1]

In the proposed method, dynamic patch size is used to obtain accurate measurement of transmission. Pixel count of 3×10^5 is considered as reference. For images having total number of pixels lesser than the reference value, patch size of 15×15 is chosen [1]. For images having pixel count equal to or more than the reference value, patch size is determined using the following expression:

$$newSize = oldSize + \left(5 \times \left\lfloor \frac{imageSize}{referenceValue} \right\rfloor\right) \quad (17)$$

Further, it is ensured that the new patch size has odd number using the following expression:

$$newSize = newSize + (1 - (newSize \ mod \ 2)) \quad (18)$$

C. Estimating Air Light

The patch size calculated using (18) has been optimized for transmission estimation but, it is not large enough to take care of localized light sources. In the presence of such sources, air light is calculated using pixels near the center of the light source.

To deal with this problem, Yi-Jui Cheng et al. [14] proposed hybrid patch size, that is, different patch size for estimating transmission and air light. Air light has been estimated using dark channel computed for patch of size 45×45. The result of their method is shown in Fig. 4.

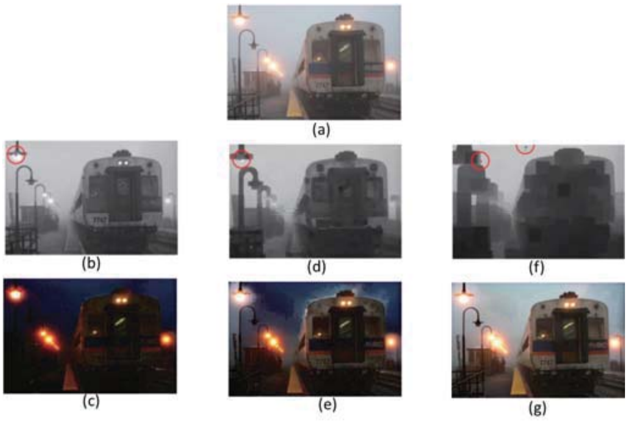

Fig. 4 (a) Input hazy Image (b) 3x3 Dark channel (c) Recovered image using 3x3 patch (d) 15x15 Dark Channel (e) Recovered image using 15x15 patch (f) 45x45 Dark Channel (g) Recovered image using 45x45 patch [11]

To handle the problem of localized light sources, the proposed method also incorporates hybrid patch size but, with a different approach as in [14]. It is not kept fixed to 45×45 but varied in accordance with size of the image. In the proposed algorithm, it is kept thrice as large as patch size calculated in step *B*. This ensures that localized light sources are never mistakenly used for estimating air light irrespective of input image size.

D. Estimating Transmission

He's method suffered from the problem of saturation for near white scenes. This happens because when dark channel of near white large objects is computed, it does not come out dark. This is due to high intensity in all the three color channels. Due to this, the near white object is considered as a far object by the algorithm, underestimating the transmission which in turn leads to over estimation of scene radiance i.e. saturation.

Feng Liu et al. [18] effectively solved this issue by increasing transmission of those pixels for which difference between the highest and lowest intensity levels is nearly the same as the average of difference in the image.

Also, He's conventional DCP method undergoes blue horizon problem, i.e., objects near the horizon appears blue. This happens because transmission is kept constant among color channel, but actually it depends on color. To overcome this issue, we computed transmission separately for each channel as [3].

$$\widetilde{t^c}(x) = 1 - \min_{y \in \Omega(x)} \left(\frac{I^c(x)}{A^c} \right) \quad (19)$$

E. Refinement Using Fast Guided Filter

We used fast guided filtering to remove halo artifacts. Replacement of soft matting by guided filter made conventional DCP algorithm very fast. To further increase the speed of guided filter, He [1] proposed to subsample the input and guiding image, perform filtering process using these subsampled images and at last up sample the final output. This is called fast guided filter. This increased the speed as compared to soft matting technique. In the proposed technique, fast guided filtering along with implementation of lifting wavelet transform resulted in significant reduction in run time.

F. Calculating Scene Radiance

Scene radiance is computed using following:

$$J(x) = \left(\frac{I(x) - A(x)}{max(t(x), t_0)} \right) + A(x) \quad (20)$$

IV. Simulation and Results

Results obtained from the proposed algorithm have been discussed and compared with the conventional methods. Quantitative and qualitative results are shown. Simulation has been performed in MATLAB software.

A. Qualitative Investigation

In Fig. 6, the mountains turn bluish near horizon when conventional DCP is used for dehazing. The proposed method solves this problem by calculating transmission separately for each color channel. Same is also observed in Figs. 7-10.

In Fig. 11, transmission of marble is under estimated in He's algorithm due to which it appears yellowish. Proposed method result shows that the saturation problem of near white scenes has been successfully dealt with.

In Fig. 12, He's method results in over saturation i.e. the natural color of cones is lost while the proposed method successfully dehazes without compromising at color fidelity.

B. Quantitative Investigation

Following parameters has been used to compare the image dehazing:

1. Entropy: It is a measure of randomness. It can characterize image texture. Image with lot of sky region or large number of pixels with similar value has low entropy. Low entropy value characterizes homogeneous regions. Thus hazy images, which have haze spread throughout, have low values of entropy as compared to haze free images. Mathematically,

$$Entropy \ H = -\sum_i p_i(log_2 p_i) \quad (21)$$

where, p_i is the histogram count. Entropy comparison in Table

I shows that proposed algorithm performs better as compared to the classical DCP method.

2. Structural Similarity Index (SSIM): It measures image degradation due to processing like image dehazing in present case. This metric requires reference image. Mathematically,

$$SSIM(x,y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)} \tag{22}$$

where, μ_x is the mean of x, μ_y is the mean of y, σ_x^2 is the variance of x, σ_y^2 is the variance of y, σ_{xy} is the variance of y, c_1 and c_2 are variables to stabilize division.

In the present work, input hazy image has been used as the reference image. Higher value of SSIM indicates that structure information is well maintained in the haze free image.

3. RMS contrast: It is calculated using:

$$RMS\ Contrast = \sqrt{\frac{1}{MN}\sum_{i=0}^{N-1}\sum_{j=0}^{M-1}(I_{ij} - \bar{I})^2} \tag{23}$$

For grayscale image of size $M \times N$, having average intensity $\bar{I}$ and intensities normalized to a range of [0,1]. Analysis in Table I shows that results obtained using proposed method has better contrast than He's method. The execution time of proposed algorithm has been compared with conventional DCP. It is shown in Table II.

V. Conclusion

In this paper, the limitations of DCP algorithm have been analyzed. Based on this analysis, a novel method based on DCP in lifting wavelet transform domain has been proposed to address some of the problematic areas like speed, blue horizon problem, localized light sources and saturation of near white scenes. The results show the effectiveness of the proposed method.

Speed has been increased using lifting wavelet scheme for Daubechies 4 wavelet and subsampling technique in guided filter. Problem of blue horizon has been dealt by computing transmission for each color channel separately. Impact of localized light sources on air light computation is minimized by using large enough patch size. On the other hand, to remove haze completely while retaining the natural feeling of scene depth, smaller patch size has been used to estimate transmission. Thus, adaptive hybrid patch size scheme has been employed. Lastly, near white scene saturation problem has been tackled by using adaptive correction factor for transmission.

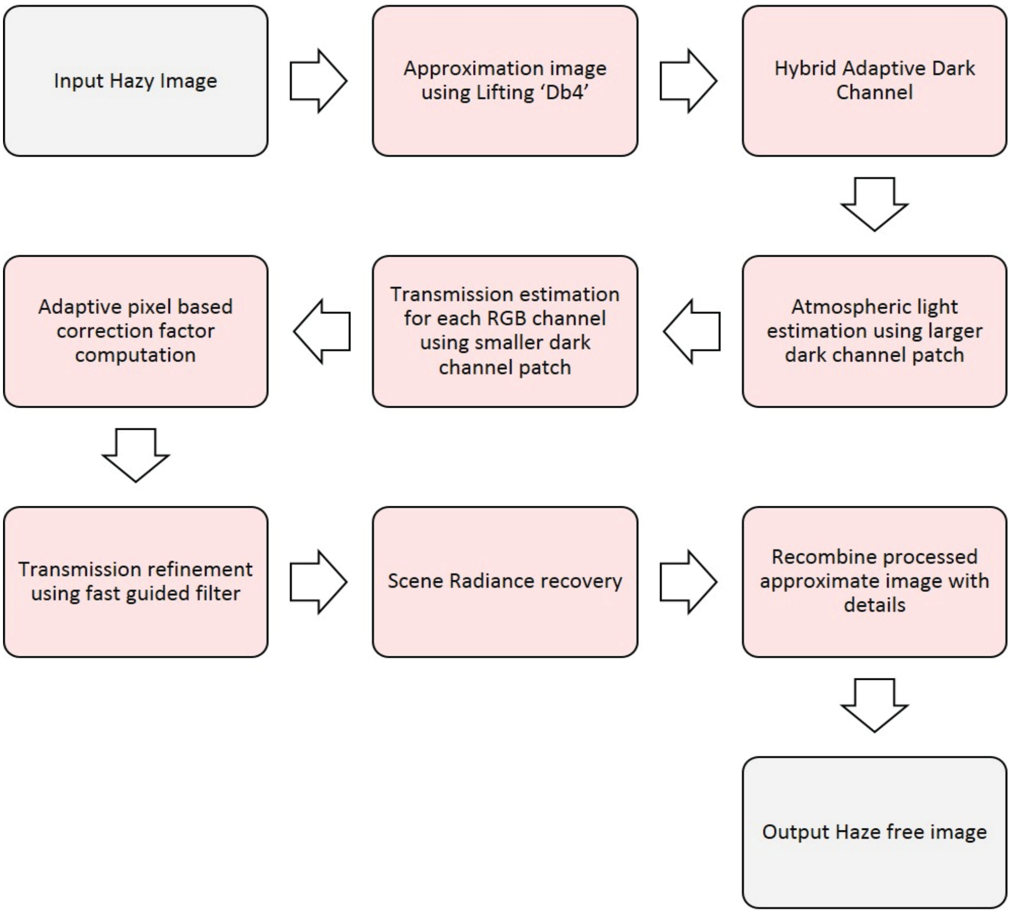

Fig. 5 Flow chart of our dehazing algorithm

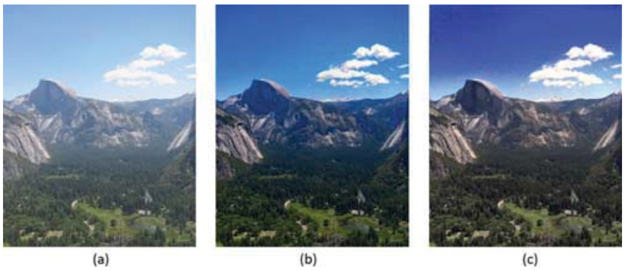

Fig. 6 Blue Horizon Problem (a) Input hazy image (b) He's output. Mountains near horizon turn blue (c) Our output. Original color of mountains remains intact

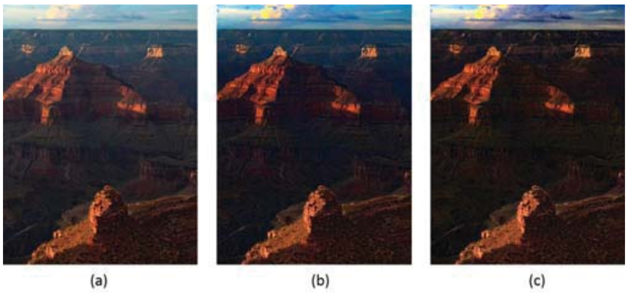

Fig. 7 Blue Horizon Problem (a) Input hazy Image (b) He's output. Canyons near horizon turn blue (c) Our output. Original color of canyons remains intact

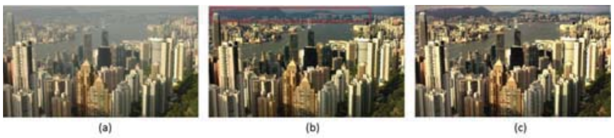

Fig. 8 Blue Horizon Problem (a) Input hazy image (b) He's output. Mountains near horizon are not clear (c) Our output. Mountains near horizon are clear and don't turn blue

Fig. 9 Blue Horizon Problem (a) Input hazy image (b) He's output (c) Our output

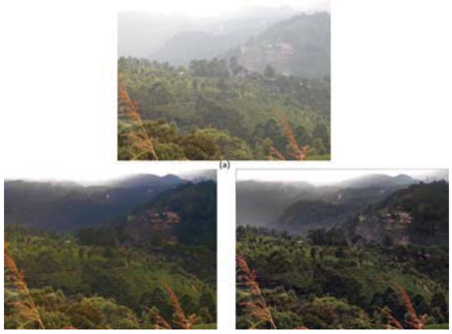

Fig. 10 Blue Horizon Problem (a) Input hazy image (b) He's output (c) Our output

Fig. 11 Near white scene saturation (a) Input hazy image (b) He's output. Marble is saturated (c) Our output. Color of marble remains intact

TABLE I
ENTROPY, SSIM AND CONTRAST COMPARISON

Parameter	***Entropy***			***SSIM***		***Contrast***		
Image	**Hazy input**	**He's Method**	**Proposed method**	**He's Method**	**Proposed Method**	**Hazy input**	**He's Method**	**Proposed method**
Fig. 6	7.58	7.62	7.19	0.69	0.63	8.06	7.16	8.31
Fig. 7	6.73	6.63	6.43	0.63	0.64	7.19	6.21	6.48
Fig. 8	7.56	7.64	7.74	0.79	0.78	7.54	9.25	9.92
Fig. 9	7.06	7.39	7.51	0.74	0.70	5.10	6.49	7.15
Fig. 10	7.56	6.88	7.05	0.65	0.63	8.37	8.07	8.90
Fig. 11	7.35	7.66	7.72	0.81	0.81	6.59	6.75	7.53
Fig. 12	7.22	7.06	7.17	0.68	0.69	5.54	4.40	5.75

Fig. 12 Saturation (a) Input hazy image (b) He's output. Cones are saturated (c) Our output. Color of cones remains intact

TABLE II
RUN TIME COMPARISON

Figure	**Image Size**	**DCP (FGF)**	**Proposed Scheme**
Fig. 6	588x742	6.865s	4.910s
Fig. 7	450x600	4.401s	3.095s
Fig. 8	800x457	5.940s	4.050s
Fig. 9	800x431	5.495s	3.784s
Fig. 10	1152x864	14.460s	9.161s
Fig. 11	400x600	3.981s	2.771s
Fig. 12	465x384	3.030s	2.173s

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