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Fast Single Image Dehazing Through Edge-Guided Interpolated Filter

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Abstract

Images and videos taken in foggy weather often suffer from low visibility. Recent studies demonstrate the effectiveness of dark channel prior [3] and guided filter [4] based approaches for image dehazing. However, these methods require high computational cost which makes them infeasible for realtime and embedding systems. In this paper, we propose Edge-Guided Interpolated Filter (EGIF) for fast image and video dehazing. The main contributions are twofold. Firstly, we develop Guided Interpolated Filter (GIF) to significantly speed up the estimation of transmission map, which is the most computational cost step in previous methods. Secondly, we utilize edge map as guidance image in GIF to enhance the fine details in dehazed images . Experimental results show that GIF can largely improve the computational efficiency and achieve comparable dehazing performance as previous guided filter based methods. EGIF can further enhance the sharpness of transmission map. Our method can achieve real-time processing for image of size 1024×768 *with single CPU core (2GHz).*

1 Introduction

Suspended impurities in atmosphere can scatter, refract, and absorb light, leading to poor visibility, low contrast and color offset of the images captured. Automatically removing haze from images has many important applications, and receives extensive research interests in recent years.

Single image haze removal is more challenging, due to its ill-posed nature. Methods along this line (Tan [9], Fattal [1], Tarel [10], He et al. [3]) often leverage image priors or assumptions. A key step in many image dehazing methods is to estimate transmission map. Meng et al.[7] formulate transmission map estimation as an optimization problem. Tang et al.[7] propose a learning framework to estimate transmission map. He et al.[4] propose guided filter to accelerate the estimation of transmission. Several approaches are proposed to improve the speed of haze removal with GPU parallel computation [5, 11],which may not be available in many practical applications, such as embedding systems.

In this paper, we develop a fast single image dehazing method to improve the celebrated guided filter based image dehazing methods [3, 4] in several aspects. Firstly, we introduce piecewise interpolation into the traditional guided filter, which can largely speed up the estimation of transmission map. More specially, we propose three types of interpolation strategies and compare them in experiments. Secondly, we leverage edge map as guided image which help to enhance the fine structures. Experimental results show that, our method can significantly accelerate dehazing speed without harming the image quality. Our method can achieve real time dehazing for 1024×768 video with single CPU core.

2 Dehazing with guided interpolated filter

The degradation of haze image can be explained by the following atmosphere scattering model [6] with two terms.

$$I(x) = J(x)t(x) + A(1 - t(x)), \tag{1}$$

The first term is direct attenuation and the second term is added airlight. x is the position of a pixel, $I(x)$ is hazy image, and $J(x)$ is haze free image we need to restore. $t(x)$ is the medium transmission and A is the global atmospheric light.

He et al.[3] analyzed mounts of haze-free images and proposed a novel phenomenon named Dark Channel Prior(DCP): In most of the non-sky patches, at least one color channel has very low intensity at some pixels. That means the minimum intensity in such a patch is close to zero. Dark channel is tend to zero for haze-free image, but approximates haze density for hazy image.

Airlight A can be estimated by picking top 0.1% brightest pixels in the dark channel, and selecting the brightest pixel. Transmission $t(x)$ can also be obtained from dark channel,

$$t(x) = 1 - w \min_{y\in\Omega(x)} \{\min_c \frac{I^c(y)}{A^c}\}, \tag{2}$$

where $w(0 < w < 1)$ indicates the percentage of haze to be removed, set to 0.95 in [3]. Latter term after w is dark channel.

Directly using the rough transmission map t calculated by Eq.(2) may lead to halos and block artifacts , so we need to refine and smooth the transmission map. Guided filter(GF) [4] can speed up refinement procedure of transmission instead of soft matting in [3]. Even so, guided filter based dehazing method cannot do real-time dehazing for videos, so we propose guided indterpolated filter to further accelerate the dehazing speed.

2.1 Guided interpolated filter(GIF)

As shown in figure 1, guided interpolated filter(GIF) takes a small size image t as input and a large size image I as guidance. Its output is a large size image T, similar to t in content and the same size as I. Let w_k denote a window centered at pixel k and i denote the index of pixel within w_k. Let W_k denote the corresponding window of w_k in large size image I and T. For pixel i in w_k, we use $j = m(i)$ to denote its corresponding pixel in W_k.

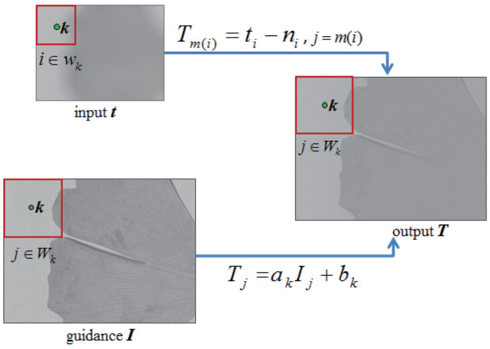

Figure 1. Illustration of Guided Interpolated Filter.

Following guided filter, a local linear model is assumed between guidance image and filtering output,

$$T_j = a_k I_j + b_k, \forall j \in W_k, \tag{3}$$

where $(a_k,\, b_k)$ are linear transformation coefficients assumed to be constant in the local window W_k. Assume a noisy model between the output and input image, $T_{m(i)} = t_i - n_i$.

Coefficients $(a_k,\, b_k)$ can be inferred by minimizing the difference between output T and input t,

$$E(a_k, b_k) = \sum_{i \in \omega_k} ((a_k I_{m(i)} + b_k - t_i)^2 + \varepsilon(a_k)^2), \tag{4}$$

where ε is a penalty parameter to avoid large a_k. The solution of minimizing Eq.(4) is given by,

$$a_k = \frac{\frac{1}{|\omega|} \sum_{i \in \omega_k} I_{m(i)} t_i - u_k \overline{t_k}}{(\sigma_k)^2 + \varepsilon}, b_k = \overline{t_k} - a_k \mu_k, \tag{5}$$

where $I_{m(i)}$ denotes the corresponding pixel of pixel t_i in small image t. μ_k and $(\sigma_k)^2$ are mean and variance of I_m in window ω_k, $|\omega|$ is the number of pixels in ω_k. $\overline{t_k^s}$ is the mean value of t in ω_k.

At last, the output T at sampled position $m(i)$ can be obtained by

$$T_{m(i)} = \overline{a_i} I_{m(i)} + \overline{b_i}, \tag{6}$$

where $\overline{a_i} = \frac{1}{|\omega|} \sum_{k \in \omega_i} a_k$ and $\overline{b_i} = \frac{1}{|\omega|} \sum_{k \in \omega_i} b_k$ are the average coefficients of all windows containing pixel i. So far, we only compute output image T at sampled positions corresponding to t. In the next, we are going to estimate values at other positions by interpolating among their neighbors. Specially, we propose three interpolation strategies:

inter-t: directly interpolating the small size transmission T_m computed by Eq.(6) to get the full size transmission T through bilinear interpolation.

inter-ab: interpolating transformation parameters $(a_k,\, b_k)$ computed by Eq.(5) through bilinear interpolation. Then large transmission T is obtained by Eq.(3).

inter-mp: interpolating intermediate variables (μ_k,σ_k and $\overline{t_k}$) in computing $(a_k,\, b_k)$ by Eq.(5) through bilinear interpolation. Then we can calculate a_k and b_k for each pixel k in large image by Eq. (5), and finally obtain T by Eq. (3) .

Compared with guided filter (GF), GIF only conducts the computational expensive operations of Eq.(5) at sampled positions and largely improves the speed of GF. Moreover, GIF allows input image and guided image have different sizes while GF requires both have the same size. This fact enlarges the possible applications of GF.

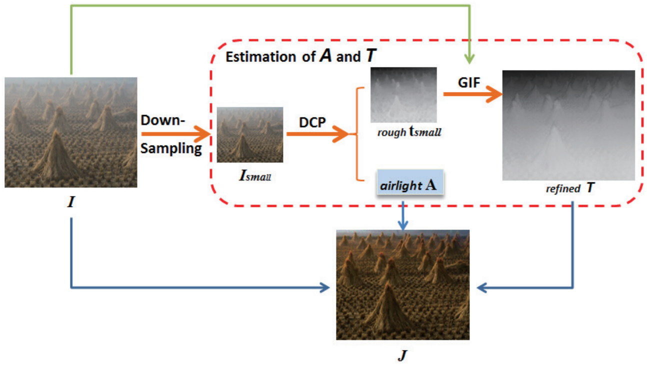

Figure 2. Framework of dehazing by Guided interpolated filter.

Figure 2 shows the framework of our dehazing method with GIF. Hazy image I is downsampled to a small size image I_{small}. The corresponded rough transmission t_{small} is computed by Dark Channel Prior(DCP), and airlight A can be obtained. GIF is used to refine and upsample the small size transmission t_{small} under guidance of the hazy image I. The output is a refined transmission T with the same size as I. At last,with estimated A and T, the recovered image J can be obtained by inverting Eq.(1).

2.2 Edge-guided interpolated filter

Like guided filter [4], GIF is also an edge-preserving filter that transfers edge information of the guidance image to the output. However, high frequency information especially edges can be lost during downsampling. In order to get a sharp transmission, we enhance edges in the guidance image, which can be further transferred to the output transmission. So the transmission appears to be sharper at edges. This improved version is named as Edge-guided interpolated filter(EGIF).

We just enhance the guidance image by adding gradients of the hazy image I_{gx},I_{gy} to hazy image I by multiplying with a factor α, see Eq.(7). Also we can try other edges, such as Sobel edges and Canny edges.

$$I_e = I + \alpha \sqrt{I_{gx}^2 + I_{gy}^2}, \tag{7}$$

3 Experiments

We collect two datasets to examine the proposed methods. Dataset1 consists of 28 hazy images commonly used in previous dehazing methods [9, 1, 3, 10]and another 59 real-world hazy images from Internet, with sizes different from 500×332 to $2,048 \times 1,536$. Dataset2 includes 358 hazy images, synthesized from

400 outdoor clear images with size $1,704 \times 2,272$ and their corresponding depth map [8]. Due to the disparity between depth and scene caused by laser scanner, the synthetic hazy images may exhibit heterogeneous fog in certain regions. Therefore, we crop image regions with reliable depth information. Compared with Dataset1, Dataset2 includes ground truth of haze-free image and transmission map.

Mean square error(MSE) and feature similarity(FSIM) [12] are used as evaluation criterion. All our experiments are implemented on a PC with a 2.93GHz Intel Core2 Duo CPU and 6GB RAM.

3.1 Comparison of interpolation strategies

We compare three interpolation strategies **inter-t**, **inter-ab** and **inter-mp** in term of dehazing performance and time cost. For dataset1, we used the transmission map and dehazed image obtained by GF as reference; while for dataset2, we used ground truth. We adopt mean square error (MSE) and feature similarity (FSIM) [12] between the reference image and the estimated image as evaluation criterion. **t-MSE** denotes the MSE of transmission map, while **img-MSE** and **img-FSIM** measure the dehazed image difference. Lower MSE or higher FSIM indicates better performance.

Table 1. Comparison of 3 interpolation strategies.

Dataset	Evalution	**inter-t**	**inter-ab**	**inter-mp**
Dataset1	t-MSE	3.485e-4	**1.856e-4**	1.857e-4
	img-MSE	1.085e-4	**6.421e-5**	6.439e-5
	img-FSIM	0.977032	**0.977288**	0.977287
Dataset2	t-MSE	6.859e-4	**6.908e-4**	6.909e-4
	img-MSE	3.834e-4	3.537e-4	**3.535e-3**
	img-FSIM	**0.999675**	0.999659	0.999660

Table 1 shows our comparison results. For Dataset1, we can see both **inter-ab** and **inter-mp** obtain transmission map and recovered image very close to guided filter, much better than **inter-t**. Performance of **inter-ab** is slightly better than **inter-mp**. For Dataset2, **inter-ab** estimates transmission more accurately than the other two in terms of MSE. As a result, all the three interpolation strategies yield good results, while **inter-ab** and **inter-mp** show better performance.

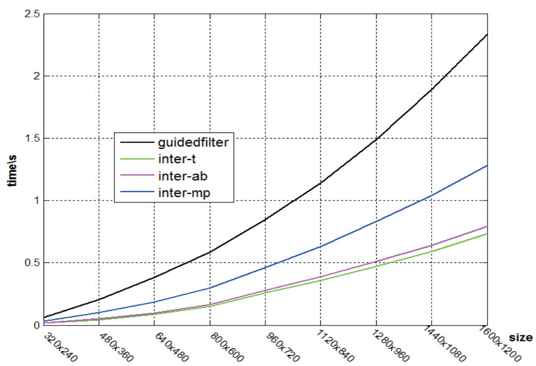

Figure 3. Recovered images by guided filter, **inter-t**, **inter-ab** and **inter-mp**.

To evaluate time efficiency, we select 22 images from Dataset2 and crop them to obtain images with 9 different sizes (320×240, 480×360, 640×480, 800×600, 960×720, $1,120 \times 840$, $1,280 \times 960$,$1,440 \times 1,080$, $1,600 \times 1,200$). Figure 3 depicts the average dehazing time cost of different sizes. We can see all the three interpolation strategies require significantly less time than GF. Among them, **inter-t** is the fastest, while **inter-ab** is a little slower but very close, and **inter-mp** is the slowest. Taking account of the above facts, **inter-ab** yields a good balance between performance and computational time. In the next, we use **inter-ab** without special notification.

3.2 Evaluation of EGIF

We have tried gradient edges, Sobel edges and Canny edges for EGIF (Section 2.2), and found gradient edges shows best performance with $\alpha = 3$. Figure 4 gives an example of the recovered images by GIF and EGIF. It can be seen that the image recovered by EGIF looks more clear and yields fine structure in the building areas.

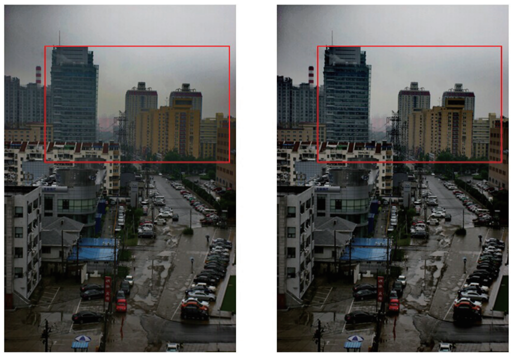

Figure 4. Left: recovered image by GIF. Right: recovered image by EGIF.

We also explore how interpolation scale influence EGIF's performance and recommend interpolation scale should be no more than 4, because dehazing performance becomes poor rapidly with interpolation scale big than 4, but time cost doesn't decrease too much.

3.3 Comparison with other dehazing methods

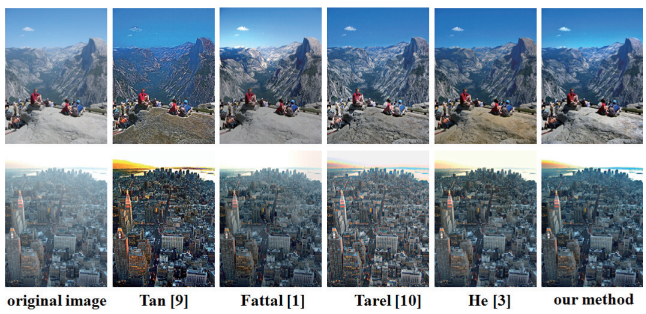

Figure 5. Recovered images by different methods.

Figure 5 displays the dehazed results for images y16 and ny12 of size 576×768 by our method and previous state-of-the-art methods [9, 1, 10, 3]. We can see that our EGIF obtains competitive results with good visibility and less distortion.

Table 2. Quantitative comparison of recovered images by different methods.

		Tan[9]	Fattal[1]	Tarel[10]	He[3]	our
y16	**e**	-0.08	0.03	-0.008	0.06	0.138
	r	2.08	1.27	2.01	1.42	1.626
	ns	0.005	0.003	0.0	0.002	0.001
n12	**e**	-0.14	-0.06	0.07	0.06	0.074
	r	2.34	1.32	1.88	1.42	1.384
	ns	0.02	0.086	0.0	0.0	0.0

Besides, quantitative evaluation on the quality of recovered images are showed in Table 2. Tarel [10] used visibility measurements **e**,**r** and **ns** to evaluate dehazing preformance, which are proposed in [2]. After dehazing, many edges become newly visible. The rate of edges newly visible **e** evaluates ability of the method to restore edges which newly appear in recovered image after dehazing. Mean ratio **r** of the gradients at visible edges estimates average contrast restoration by dehazing method. The percentage of pixels **ns** which becomes completely black or completely white after restoration should be small if the dehazing method shows good performance. Our method shows good performance in terms of both **e** and **ns**, which means more edges become visible and less pixels become completely black or white. For evaluation **r**, Tan [9] shows highest score, which maybe caused by maximizing local contrast. Our method shows comparable score with other methods. So in a word, our method shows great performance in the recovered image.

Table 3. Computational time of different methods.

size	He's[3]	Fattal[1]	Tarel[10]	He's[4]	ours
441×450	18.67m	26.496s	0.521s	1.512s	**0.016**s
384×399	13.11m	20.457s	0.362s	1.104s	**0.015**s
651×509	39.87m	44.241s	1.076s	3.193s	**0.031**s

Table 3 compares the computational cost between our method and others [3, 1, 10, 4]. We use the implementation from the authors of [3, 4] and the time cost of methods [1, 10] came from [11]. It can be seen that our method is much faster than all the compared methods. GIF improve the speed more than 20 times compared with baseline GF [4]. Moreover, our method can do real-time dehazing on videos of size 1024×768 with singe CPU core (2Ghz) when interpolation scale is 4.

4 Conclusion

This paper proposes Edge-Guided Interpolated Filter(EGIF) for fast image dehazing. Compared with guided filter, GIF can significantly improve the dehazing speed without influencing the quality of recovered images. EGIF utilizes edge-enhanced image as guidance which proves to be helpful in improving the fine structure of dehazed images. Our method enables to conduct real-time dehazing for 1024×768 videos. As for future work, we are going to study the dehazing problem in the difficult situations such heavy fog, nonuniform cloud etc. One challenging here is that the ideal atmosphere scattering model [6] may not hold in these situations.

Acknowledgement

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