Algorithmic Development of Edge-Preserving Filters for Single Image Dehazing

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by

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Chapter 7

Conclusions

The primary objective of this dissertation is to improve the visibility and visual quality of hazy images by developing some edge-preserving filters. When images are captured in hazy or foggy conditions, they tend to have reduced contrast, color saturation, and overall clarity, making it difficult to perceive details and objects at a distance. Edge-preserving filtering is a technique used in image processing to reduce haze while preserving the edges and fine details in the scene. The main goal is to remove the unwanted haze or fog while retaining the sharpness and clarity of the objects and structures in the image.

Edge-preserving filters, such as guided image filter (GIF), weighted guided image filter (WGIF), gradient guided image filter (GGIF), effective guided image filter (EGIF), etc., are employed to achieve this objective. These filters consider the local pixel intensity and spatial information, allowing them to differentiate between haze and actual image features. By preserving edges and avoiding over-smoothing, the dehazed image becomes visually pleasing and useful for various applications like computer vision, object detection, and surveillance systems. Edge-preserving filters are often used in dehazing algorithms to refine the transmission map, which is a crucial step in haze removal from a hazy image. The transmission map represents the extent to which each pixel in the image is affected by the haze or atmospheric scattering. In a hazy scene, objects at a distance appear hazier compared to those closer to the camera. The transmission map determines the amount of haze or fog present at different locations in the image. Edge-preserving filters work by selectively smoothing the transmission map while preserving sharp edges and details in the scene. By doing so, they can effectively separate the haze information from the actual scene content. This helps in accurately estimating the underlying scene radiance, which is a clean version of the hazy image. Once the transmission map is refined using edge-preserving filtering techniques, it is used to perform the actual dehazing process. By attenuating the haze effect based on the refined transmission map, the algorithm can restore the visual quality of the image, making objects and details more visible and improving overall visibility. It's worth mentioning that the dehazing process can involve additional steps, such as estimating the atmospheric light and applying a dehazing model to the image. However, the use of edge-preserving filters in refining the transmission map is a key component in many single image dehazing methods to achieve accurate and visually appealing results.

Chapter 1 dealt with the introduction of the dissertation, haze effects in atmospheric scattering models, haze imaging model and important terms related to image dehazing are discussed in detail. Further, motivation, challenges and research problems are presented in this chapter.

Chapter 2 presented state-of-the-art works, background and related preliminaries for single image dehazing in details. The experimental set-up, datasets, and relevant referenced and non-referenced quantification parameters used in this dissertation are discussed in detail.

In **Chapter 3** an effective scale-aware edge-smoothing weighting constraint-based weighted guided image filter (ESAESWC-WGIF) is presented for single image dehazing. The proposed method is multi-scale local linear transform model based edge-smoothing filter. It removes halos, over-smoothing strongly and preserves edge-details precisely in both flat and sharp regions. The proposed filter is less sensitive to the regularization parameter (ε) as comparison to the existing edge-preserving GIF, WGIF, GGIF, and EGIF methods. Therefore, the proposed method preserves edge-details in sharp regions more accurately. The performance of the proposed method is tested on about 3,200 images from real time hazy, non-real time hazy, synthetic hazy, dense hazy and night time hazy images of Fattal, NYU2, D-HAZY, Haze-RD, O-HAZE datasets and resulting outcomes are compared with 7 state-of-the-art DCP, GIF, WGIF, GGIF, EGIF, DehazeNet and RYF-Net methods. The experimental results prove that the proposed method restore the images with excellent color, contrast and visual quality.

Moreover, the proposed method is independent of the nature of the input image. It performs equally well for all datasets as compared to the existing dehaze methods. Further, to analysis the enhancement feature of the restored image, a blind object evaluation metric is used to calculate score of the proposed filter for different values of the regularization parameter ε and compared with the existing GIF, WGIF, GGIF and EGIF methods. To asses the effectiveness of the proposed method, quantification parameters such as: PSNR, SSIM, FADE and CIEDE2000 are evaluated for natural hazy, non-hazy and synthetic images from Fattal, NYU2, D-HAZY, Haze-RD, O-HAZE datasets and results are compared with different existing DCP, GIF, WGIF, GGIF, EGIF, DehazeNet and RYF-Net methods. Next, the average execution time of the proposed method and the existing DCP, GIF, WGIF, GGIF, EGIF, DehazeNet, and RYF-Net methods are computed for five images having resolution 250×200, 550×400, 850×600, 1000×950 and 1400×1200.

In **Chapter 4**, a new robust scale-aware weighting-based effective edge-preserving gradient domain guided image filter (RSAW-EEPGDGIF) is proposed for single image dehazing. Edge-preserving gradient guided filter is a type of image processing filter which remove haze from input image more accurately and efficiently than the existing GIF, WGIF and EGIF methods. This filter remove haze effectively without blurring the edges. It is a local optimization based effective edge-preserving filter. The proposed filter refines transmission map by decomposing it into effective weighted base layer (EWBL) and effective weighted detail layer (EWDL), respectively. Further, EWBL and EWDL of the proposed method are calculated with different regularization parameter values and the results are compared with different existing edge-preserving filters. The proposed method is used a sigmoid function based non-linear mapping function (NLM) to suppress various artifacts and noises and enhance the gradient information in EWDL.

The performance of the proposed method is tested on hazy, non-hazy and synthetic images from different datasets viz. Fattal, D-HAZY, Middlebury, Haze-RD, Image-Net, NYU2, FRIDA, O-HAZE and their outcomes are compared with existing DCP, GIF, WGIF, GGIF, EGIF, AnisGF, SKWGIF, ADMEF, AMEIF, AOD-Net, RYF-Net, PMHLD and RefineDNet methods. To analysis the effectiveness of the proposed method, we have used four different values of $\zeta_1 = (5, 15, 30, 60)$ and fixed regularization parameter $\varepsilon = 0.1^2$. It is evident from the results that visibility of halo artifacts decrease for higher values of ζ_1 and halos in sharp regions are more visible for a small ζ_1 value as compared to the large ζ_1 value. Moreover, the proposed method removes halo artifacts strongly than the existing GIF, WGIF, GGIF, EGIF, AnisGF, SKWGIF methods. Finally, qualitative analysis proved that the proposed method is independent of the nature of image and it performs equally well for all datasets as compared to the existing image dehazing methods.

The proposed method has been tested on about 1,690 images from Fattal, D-HAZY, Middlebury, Haze-RD, Image-Net, NYU2, FRIDA, O-HAZE datasets and the dehaze outcomes are compared with 13 state-of-the-art haze removal methods out of which is prior-based dehaze method, GIF, WGIF, GGIF, EGIF, AnisGF, SKWGIF are edge-preserving filter based haze removal methods, ADMEF, AMEIF are fusion based dehazing methods, and AOD-Net, RYF-Net, PMHLD and RefineDNet are deep learning based haze removal methods. The visual comparison of the proposed method with the existing dehaze methods are calculated for window size ζ_1=15 and fixed regularization parameter $\varepsilon = 0.1^2$. It is clear from dehazed results that in the existing methods, over-smoothing increases with the increase in the regularization parameter ε. However, the proposed method does not suffer with such a problem. It proves that the proposed method removes halo artifacts, over-smoothing strongly and preserve edge information more accurately in both flat and sharp regions than the existing methods. Since the proposed method is independent of the nature of image, it performs well on all the aforesaid datasets than the existing methods. The qualitative analysis also prove that the proposed method restore the haze free image with excellent visual quality.

The performance metrics e, $\overline{r}$, $\overline{\alpha}$, contrast gain C_g, visual contrast measurement (VCM), structural similarity index (SSIM), peak signal to noise ratio (PSNR), edge keeping index (EKI), color difference metric CIEDE2000, fog aware density evaluator (FADE), color natural index (CNI), and universal image quality index (UIQI) are used to assess the effectiveness of the proposed method more judiciously. In addition to these metrics, the average execution time of the proposed method is calculated and outcomes are compared with the existing methods. In this analysis, 10 images from each dataset with resolutions of 185 $\times$ 231, 384 $\times$ 512, 512 $\times$ 768, 600 $\times$ 450, 1600 $\times$ 1200, 2592 $\times$ 1944, 2144 $\times$ 1424, and 2300 $\times$ 1600 were selected. Results of average execution time demonstrate that the proposed method requires less processing time as compared to the existing methods. The box plot based statistical assessment of the proposed method for different performance metrics also prove that performance of the proposed method is better than the existing methods. From all these facts, it is clear that the proposed method removes halo artifacts, over-smoothing, color distortion strongly and preserves edge information precisely in both flat as well as sharp regions.

In **Chapter 5**, a non-local haze line averaging (NL-HLA) based a new robust multi-scale weighting edge-smoothing filter (RMWEF) is proposed for single image dehazing. In this Chapter, NL-HLA algorithm is applied on initial transmission map to remove morphological artifacts. In RMWEF, a new multi-scale weighting is incorporated in the cost function of GGIF to refine the transmission map more accurately than the existing dehaze methods. It refines the initial transmission map by decomposing it into the base layer (BL) and detail layer (DL), respectively. It is a local edge-preserving smoothing filter which removes over-smoothing effect strongly in the areas with fine structures and preserves details in such areas very well at large window radius $\zeta_1 = 60$. As expected, we obtain $a_{x',y'} = 1$ for $\gamma_{x',y'} = 1$ to preserve edge information in sharp regions and it is close to 0 for $\gamma_{x',y'} = 0$ to preserve edge information in flat regions. Further, the base- and the detail- layer for a non-hazy tulip image is calculated for four different values of regularization parameter $\varepsilon = 0.001^2$, $\varepsilon = 0.01^2$, $\varepsilon = 0.1^2$, $\varepsilon = 5^2$. Results prove that the proposed method removes halo artifacts strongly and avoid over smooth in images even for large regularization parameter.

Next, the 1-D illustration between pixel intensity and pixel coordinates in the horizontal as well as in the vertical directions for tulip image are calculated for GIF, WGIF, GGIF, EGIF and the proposed method at $\zeta_1 = 60$ for three different ε values 0.01^2, 0.1^2, and 1^2, respectively. It is clear that the output pixel values of the proposed method are more closer to the input pixel values even with large ε values, whereas those are far apart in case of the other existing methods. This analysis prove that the proposed method removes halo artifacts strongly and preserves edge information precisely in both flat as well as sharp regions.

The effectiveness of the proposed haze removal algorithm is tested on on about 6618 images using different sets of hazy, non-hazy, and synthetic images of indoor training set (ITS), outdoor training set (OTS), synthetic objective testing set (SOTS), real-world task-driven testing set (RTTS) and hybrid subjective testing set (HSTS), respectively. Further, Fattal's dataset, D-HAZY dataset, Middlebury dataset, NYU dataset, FRIDA dataset are also used for better analysis and the results are compared with 9 existing dehaze algorithms GIF, WGIF, EPDSID, GGIF, EGIF, DN, RYF-Net, PMHLD and IDNPAB. To asses the effectiveness of the proposed algorithm, some of the non-referenced, referenced performance quantitative metrics and the execution time (T/s) are calculated for GIF, WGIF, EPDSID, GGIF, EGIF, DN, RYF-Net, PMHLD and IDNPAB. The non-referenced performance metrics such as the contrast enhancement $(e, \overline{r}, \overline{\alpha})$, color natural index (CNI) and fog aware density evaluator (FADE) are calculated. The peak signal to noise ratio (PSNR), structural similarity index (SSIM), CIEDE2000 and the universal image quality index (UIQI) are the reference based performance metrics. The qualitative and quantitative results are obtained for the proposed method and existing GIF, WGIF, EPDSID, GGIF, EGIF, DN, RYF-Net, PMHLD and IDNPAB methods for RESIDE subsets and Fattal's dataset, D-HAZY dataset, Middlebury dataset, NYU dataset, FRIDA dataset for three different ε values (0.01^2, 0.1^2, 1^2) and fixed window size $\zeta_1 = 60$. It can be concluded from the quantitative analysis that the performance of the proposed method is the best than the existing methods.

Next, the execution time of the proposed method is compared with the existing methods for images with different resolutions such as: 185×260, 375×512, 512×810 and 810×1100. The proposed method is faster than the existing methods for a given resolution of images. Overall, it can be concluded that the proposed method strongly removes halo artifacts and preserves edge information more accurately than the existing methods.

In **Chapter 6**, an effective edge-aware weighting filter-based structural patch decomposition multi-exposure image fusion method is presented for single image dehazing. The structural patch decomposition-based multi-exposure image fusion (SPD-MEF) algorithm use patch of hazy image instead of individual pixels. SPD-MEF method generates noise free weight map. So, improved visual quality is achieved without any kind of post processing step. The SPD-MEF method consistently produces better quality fused images for static scenes qualitatively and quantitatively. The proposed EEAWGIF refined the weight maps of each SPD-MEF image patches for effective image dehazing. The performance of the proposed method is tested on about 4,119 images of indoor real hazy, outdoor real hazy, indoor synthetic hazy, outdoor synthetic hazy, and nighttime hazy images from various datasets, viz. D-HAZY, NYU2, HazeRD, O-HAZE, I-HAZE, NH-HAZE, RESIDE-ITS, RESIDE-OTS, RESIDE-HSTS, Fattal, Night-time hazy, and their results are compared with the 14 existing DCP, CAP, DSPP, CEP, BDPK, IDBP, AMEIF, AIFASD, FFDHAIP, JCEEFID, RefineDNet, TMSGAN, EANet, MSAFFNet haze removal methods for effective analysis. It is clearly visible from dehazed outcomes that the proposed method removes halo artifacts, over smoothing strongly and preserves edge information more precisely in both flat and sharp regions than the existing DCP, CAP, DSPP, CEP, BDPK, IDBP, AMEIF, AIFASD, FFDHAIP, JCEEFID, RefineDNet, TMSGAN, EANet, and MSAFFNet haze removal methods. The proposed method is independent of the nature of image and it performs equally well for all the aforesaid datasets as compared to the existing methods. Finally, it is clear from these figures that the proposed method removes halo effect, over smoothing more strongly and preserve edge information precisely in both flat and sharp regions as compared to the existing methods.

In order to show the effectiveness of the proposed method than the existing DCP, CAP, DSPP, CEP, BDPK, IDBP, AMEIF, AIFASD, FFDHAIP, JCEEFID, RefineDNet, TMSGAN, EANet, and MSAFFNet haze removal methods, three full reference image quality assessment (FR-IQA) metrics and three no reference image quality assessment (NR-IQA) metrics are evaluated for 11 datasets viz. D-HAZY, NYU2, HazeRD, O-HAZE, I-HAZE, NH-HAZE, RESIDE-ITS, RESIDE-OTS, RESIDE-HSTS, Fattal, Night-time hazy. The peak signal to noise ratio (PSNR), structural similarity index (SSIM), CIEDE2000, contrast gain (C_g) are FR-IQA metrics and fog aware density evaluator (FADE), Blind image quality index (BIQI), Natural image quality evaluator (NIQE) are NR-IQA metrics.

Next, we analyzed the effect of edge-preserving factors, regularization parameter ε, and a parameter T for dehazing quality and fusion performance. To assess the impact of edge-preserving factors including regularization parameter ε, we first calculate the average SSIM, and FADE values of the proposed method on 10 real hazy images from RESIDE-HSTS dataset by varying ε and T. In the first set, we fixed the regularization parameter $\varepsilon = 0.25$ and varying $T = 0.1$, 0.3, 0.4, 0.6 and 0.8, while in the second set, we fixed parameter $T = 1$ and varying $\varepsilon = 0.06$, 0.18, 0.26, 0.35, and 0.43, respectively. It is observed from the results that SSIM decreases with decreasing ε and T values. On the other side, it can achieve highest SSIM for high ε and T value resulting the visual quality degraded and detail loss persist in the fused outcomes.

Further, the average running time of the proposed method is calculated and compared with the existing DCP, CAP, DSPP, CEP, BDPK, IDBP, AMEIF, AIFASD, FFDHAIP, JCEEFID, RefineDNet, TMSGAN, EANet, and MSAFFNet haze removal methods for 55 hazy images (5 images from 11 dataset) having resolution **185×231**, **384×512**, **512×768**, **600×450**, **1600×1200**, and **2592×1944**, respectively. Results prove that the proposed method is faster than the existing methods for a given resolution of images. Finally, qualitative analysis proves that the proposed method is independent of the nature of image and it performs equally well for all datasets as compared to the existing dehaze methods. Further, the performance comparison of the four proposed methods are listed in Table 7.2.

TABLE 7.1: The performance comparison of the proposed methods

Sr. No.	Proposed methods	Total Images	Datasets	Computational complexity	Methodology	Limitation	PSNR	SSIM	FADE	CIEDE 2000
1.	ESAESWC -WGIF	3200	5	O(N)	Single-scale edge aware weighting constraint with WGIF	Not applicable for dense haze and night hazy image	34.05	0.9536	0.508	3.15
2.	RSAW -EEPGDGIF	1690	8	O(N)	Multi-scale edge-aware weighting with GDGIF	Not applicable for dense hazy image	38.24	0.9285	2.15	21.51
3.	RMWEF	6618	14	O(N)	Non-local haze line averaging with Multi-scale edge-aware weighting constraint	Strong texture and low resolution based images get darkened	37.11	0.8753	0.19	6.46
4.	SPD-MEF -EEAWGIF	4119	11	O(N)	Structural patch decomposition multi-exposure image fusion based weighting constraint with WGIF	Over smoothing in sharp regions for dense hazy images	35.15	0.968	0.308	1.14

The original contributions of this dissertation are:

- A novel effective scale-aware edge-smoothing weighting constraint-based weighted guided image filter is proposed for single image dehazing. In this algorithm, the proposed weighting constraint is incorporated into the cost function of guided image filter. It is a multi-scale edge-weighting filter. The main objective of this filter is to removes halos and over-smoothing effect strongly and preserves edge-details in both smooth and sharp regions.

- A new robust scale-aware weighting based effective edge-preserving gradient domain guided image filter (RSAW-EEPGDGIF) is proposed for single image dehazing. This filter refines the transmission map by decomposing it into effective weighted base layer (EWBL) and effective weighted detail layer (EWDL), respectively. Further, a sigmoid function-based non-linear mapping function (NLM) is employed to suppress the various artifacts and noises as well as enhance the gradient information in EWDL.

- A non-local haze line averaging (NL-HLA) based robust multi-scale weighting edge-smoothing filter (RMWEF) is proposed for single image dehazing. In this filter, a new robust multi-scale edge-weighting is incorporated into the cost function of gradient guided image filter (GGIF). The objective of this filter is to remove morphological artifacts and over-smoothing effect more strongly and preserves edge-details precisely in both flat and sharp regions than the existing edge-preserving filters.

- A new structural patch decomposition-based multi-exposure image fusion (SPD-MEF) with an effective edge-aware weighting filter is proposed for single image dehazing. In this method, the proposed edge-aware weighting refine the weight maps of each decomposed image patch accurately.

- The performance of the proposed method with different existing haze removal methods are tested on indoor real hazy, outdoor real hazy, indoor synthetic hazy, and nighttime hazy images of different datasets. To asses the effectiveness of the proposed method, some full referenced and non-referenced quantification parameters are used to assess the effectiveness of the proposed method.

The future scope of edge-preserving filtering based image dehazing holds promising opportunities for further advancements in the field of image dehazing. Some potential directions for future research and development are as follows:

- Explore and develop more advanced edge-preserving filtering methods that can better preserve fine details and textures in dehazed images.
- Address the challenges of noise and artifacts that may arise during the dehazing process with edge-preserving filters.
- Investigate the robustness of edge-preserving dehazing techniques in challenging scenarios, such as extreme haze, complex lighting conditions, or low-contrast scenes.
- Development of real-time edge-preserving filtering algorithms for dehazing. This would allow the application of these techniques in real-world scenarios, such as video dehazing or live image processing.
- Develop objective metrics to quantitatively assess the performance of edge-preserving filtering methods for image dehazing, enabling better comparison and benchmarking.

By focusing on these aspects, the field of edge-preserving filtering based image dehazing can continue to progress, leading to more effective and efficient dehazing solutions with broader applications in various domains, including photography, video processing, surveillance, and remote sensing.