Single Image Fog Removal Using Bilateral Filter

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***Abstract*—In this paper, a novel and efficient fog removal algorithm is proposed. Fog formation is due to attenuation and airlight. Attenuation reduces the contrast and airlight increases the whiteness in the scene. Proposed algorithm uses bilateral filter for the estimation of airlight and recover scene contrast. Qualitative and quantitative analysis demonstrate that proposed algorithm performs well in comparison with prior state of the art algorithms. Proposed algorithm is independent of the density of fog and does not require user intervention. It can handle color as well as gray images. Proposed algorithm has a wide application in tracking and navigation, consumer electronics and entertainment industries.**

***Index terms*: Image enhancement, fog removal, airlight, bilateral filter, image contrast.**

I. Introduction

Poor visibility degrades the perceptual image quality as well as the performance of the computer vision algorithms such as surveillance, object detection, tracking and segmentation. Poor visibility in bad weather such as fog, mist and haze caused by the water droplets present in the air. These droplets are very small($1 - 10\ \mu m$)[1] and steadily float in the air. Due to the presence of fog, mist and haze light scattered in the atmosphere before it reaches the camera. Here onwards the word fog will be used for all fog, mist, and haze. Two fundamental phenomena which cause scattering are attenuation and airlight [2]. A light beam travels from a scene point through the atmosphere, gets attenuated due to the scattering by the atmospheric particles, this phenomena is called attenuation which reduces the contrast in the scene. Light coming from the source is scattered by fog and part of it also travels towards the camera and leads to the shift in color. This phenomena is called airlight. Airlight increases with the distance from the object.

It is noted that fog effect is the function of the distance between camera and object. Hence removal of fog requires the estimation of depth map or airlight map. If input is only a single foggy image then estimation of depth map is an under constrained problem. Stereoscopic estimation of depth require two images. Therefore many methods have been proposed which use multiple images. In [3] Schechner et al proposed a method based on polarization. This method removes fog through two or more images taken with different degrees of polarization. But this method can not be applied on existing databases. In past few years many algorithms [4]-[10] have been proposed for the removal of fog which use single image. In [6] Fattal proposed a method which is based on the independent component analysis (ICA). This method estimates the optical transmission in hazy scenes. Based on this estimation, scattered light is eliminated to increase scene visibility and recover haze from scene contrasts. Here restoration is based on the color information, hence this method is not applicable for gray image. This method fails when there is a dense fog because dense fog is often colorless. In [7] Tan proposed a method based on spatial regularization from a single color or gray scale image. Tan removed fog by maximizing local contrast of the image but restored image looks over saturated. Kopf et al [8] proposed a method based on the use of a 3D model of the scene. This method is application dependent and requires the interactions with an expert. He et al [9] proposed a method based on the matting and dark channel prior from a single color or gray scale image. But when the scene objects are bright similar to the atmospheric light, underlying assumptions of this algorithm are not valid. Tarel et al [4] proposed a fast visibility restoration algorithm. This method assumes airlight as a percentage between local standard deviation and local mean of the whiteness. This method based on linear operations but requires many parameters for the adjustment. In [5] Fang et al proposed a method based on the graph based segmentation. Here graph based image segmentation is applied to segment the foggy image. Then initial transmission map is obtained according to the blackbody theory. After that, a bilateral filter is used to refine the transmission map. It is noted that for the foggy image choice of segmentation control parameters is difficult.

In this paper, a novel fog removal algorithm is proposed. Present article demonstrates the efficacy of bilateral filter [11] for estimating the image depth map. Proposed algorithm achieves better results than other existing algorithms. Proposed algorithm, requires pre and post processing steps. Histogram equalization is used as a pre processing. This pre processing increases the contrast of the image prior the fog removal and results better estimation of airlight map. Histogram stretching is used as a post processing, which increases contrast of the fog removed image which is more often a low contrast image. Transfer function of the stretching is adjusted according to the image content. Proposed algorithm does not require any user intervention and is applicable for color as well as gray

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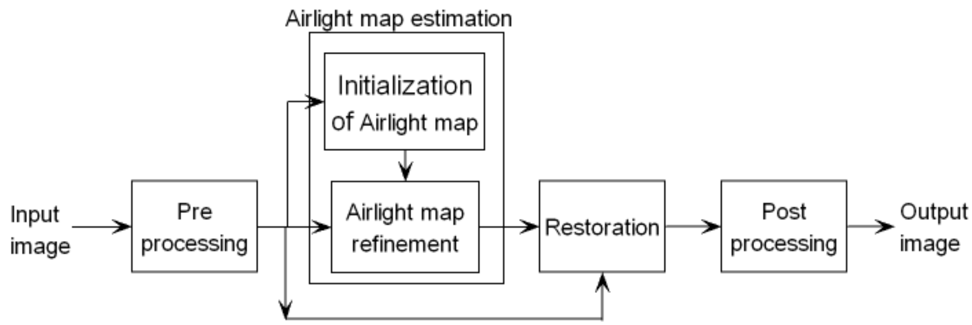


Fig. 1: Block diagram of proposed fog removal algorithm.

images. Novelties in proposed algorithm are due to its new dark channel assumption (detailed in section II-A), and pre & post processing operations (detailed in section II-D) for better estimation.

This paper is organized as follows. In Section II proposed fog removal algorithm is explained in detail. In Section III metrics used for the performance analysis are discussed. In Section IV simulation and results are discussed. Here performance of the proposed algorithm is compared with prior state of the art algorithms. Section V concludes this paper.

II. Fog removal algorithm

Fog attenuation is represented as

$$I_{att}(x,y) = I_0(x,y)e^{-kd(x,y)} \tag{1}$$

where, $I_{att}(x,y)$ is the attenuated image intensity (gray level or RGB) at pixel (x,y) in presence of fog, $I_0(x,y)$ is the image intensity in absence of fog, k is the extinction coefficient and $d(x,y)$ is the distance of the scene point from the viewer or camera.

Airlight is represented as

$$A(x,y) = I_\infty(1 - e^{-kd(x,y)}) \tag{2}$$

where I_∞ is the global atmospheric constant. It is also called sky intensity. According to the Koschmieder's law [2]-[4], the effect of fog on pixel intensity is represented as

$$I(x,y) = I_{att}(x,y) + A(x,y) \tag{3}$$

where, $I(x,y)$ is the observed image intensity at pixel (x,y).

By using (1) and (2) in (3), Koschmieder's law may be represented as

$$I(x,y) = I_0(x,y)e^{-kd(x,y)} + I_\infty(1 - e^{-kd(x,y)}) \tag{4}$$

where, in right hand side, first term is direct attenuation and second term is airlight. According to (2)

$$e^{-kd(x,y)} = \left(1 - \frac{A(x,y)}{I_\infty}\right) \tag{5}$$

Thus

$$I(x,y) = I_0(x,y)\left(1 - \frac{A(x,y)}{I_\infty}\right) + A(x,y) \tag{6}$$

Here, for simulation original foggy image $I(x,y)$ is normalized and sky intensity I_∞ is set to $[1,1,1]$. To restore image $I_0(x,y)$, information of airlight map A is needed. This airlight depends upon the depth of the scene.

Block diagram of proposed fog removal algorithm is shown in Fig.1. In order to remove fog, first as a pre processing step, histogram equalization is performed over foggy image. This pre processing step results better estimation of airlight map. Then initial value of airlight map is estimated. Final airlight map is refined using bilateral filter. Once airlight map is obtained, image is restored using (6). Histogram stretching of output image is performed as post processing step. This histogram stretched image is final de-foggy image.

A. Initialization of Airlight map

It is known that airlight map A is a scalar image which is always positive, hence $A > 0$. Taking minimal across each color component in (6), we get

$$A(x,y) = \min_{c\epsilon(r,g,b)}(I^c(x,y)) - \min_{c\epsilon(r,g,b)}\left[I_0^c(x,y)\left(1 - \frac{A(x,y)}{I_\infty}\right)\right] \tag{7}$$

According to dark channel prior [9], dark channel is denoted as the minimum intensity across red, blue and green channels. Proposed dark channel assumption differs from the proposed by He et al.[9]. Proposed dark channel is using temporal window i.e. minimum across R, G, and B channels at the particular pixel location instead of spatiotemporal 3D window proposed earlier. This modification reduces calculation significantly without loss of quality. Natural outdoor images are usually full of shadows and colorful objects (viz. green grass, trees, red or yellow plants and blue water surface). Thus dark channels of these images are really dark. For fog free image, except for sky region intensity of the dark channel is low and tends to be zero [9]. Hence $\min_{c\epsilon(r,g,b)}(I_0^c(x,y)) \approx 0$ and positive. Thus

$$\min_{c\epsilon(r,g,b)}(I^c(x,y)) \geq A(x,y) > 0 \tag{8}$$

Thus initial estimation of A can be assumed as

$$A(x,y) = \beta \min_{c\epsilon(r,g,b)}(I^c(x,y)) \tag{9}$$

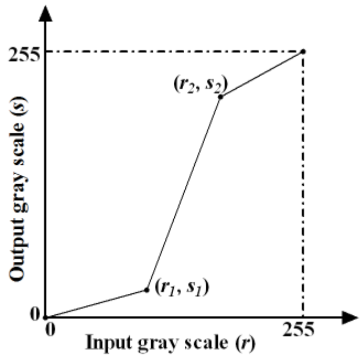


Fig. 2: Transformation function for histogram stretching.

where β is a constant and $0 < \beta < 1$. If input image is a gray scale image then initial estimation of A can be assumed as

$$A(x, y) = \beta I(x, y) \tag{10}$$

B. Airlight map refinement

Airlight map is the function of the distance between object and camera. Different object may be at different distance from camera and thus airlight should be different for different object. Also it must be smooth for an object except along the edges. Hence airlight map undergo intra-region smoothing preferentially over inter-region smoothing. The said requirements can be fulfilled by bilateral filter [11].

The discrete version of the kernel of a bilateral filter can be expressed as

$$A(\vec{n}) = \frac{\sum_{\xi \epsilon \eta_{\vec{n}}} w(\xi - \vec{n}) c(A_0(\xi) - A_0(\vec{n})) A_0(\xi)}{\sum_{\xi \epsilon \eta_{\vec{n}}} w(\xi - \vec{n}) c(A_0(\xi) - A_0(\vec{n}))} \tag{11}$$

where ξ is the pixel position, $A(\vec{n})$ is the estimate of the current pixel $A_0(\vec{n})$, $\eta_{\vec{n}}$ represents the neighborhood of $\vec{n}$ (where ξ is a member of that neighborhood), $w(\vec{n})$ and $c(\vec{n})$ and are the spatial domain and intensity domain kernels, respectively. The kernel $w(\vec{n})$ averages the neighboring pixel intensity values with decreasing weights for pixels at larger distances. The kernel $c(\vec{n})$ takes into account the intensity differences between the center pixel and its neighboring pixels; the larger the pixel value difference, the smaller is the neighbor pixels contribution during smoothing. In this way, every pixel is replaced by the weighted mean of its neighbors.

C. Restoration

Once airlight map $A(x, y)$ is estimated then each color component of de-foggy image $I_0(x, y)$ can be restored as

$$I_0(x, y, c) = \frac{(I(x, y, c) - A(x, y))}{\left(1 - \frac{A(x,y)}{I_\infty(c)}\right)} \tag{12}$$

where $c \ \epsilon \ (r, g, b)$. It is noted that proposed algorithm can also be applied for gray scale image. Only difference is the initialization of airlight map as shown in (9) and (10).

D. Post processing

Restored image may have low contrast. Thus there is a requirement of some post processing. There can be number of choices for post processing like histogram equalization, histogram specification and histogram stretching. The main drawback with histogram equalization is that output image looks saturated. For histogram specification, there is a requirement of a reference image. Moreover, due to the large variations in image contents, a standard reference image may not serve the purpose. Thus to increase contrast, histogram stretching of restored image is performed. Transformation function is shown in Fig.2. Horizontal axis r represents input pixel value, and vertical axis s represents output pixel value. In this transformation, there are three straight line segments. The parameters specifying the contrast stretch mapping are r_1, s_1, r_2, s_2, which determine the position of the intermediate straight line segment. Modifying any of these four values modifies contrast stretching transformation.

III. Performance Metrics

Performance of proposed algorithm is compared with other existing algorithms in terms of the contrast gain (C_{gain}) [12] and percentage of saturated pixels (σ) [13].

A. Contrast gain

Contrast gain (C_{gain}) is described as follows. Let an image of size $M \times N$ is denoted by $X(x, y)$. Then, contrast of the pixel (x, y) is expressed as

$$C(x, y) = \frac{l_2(x, y)}{l_1(x, y)} \tag{13}$$

where

$$l_1(x, y) = \frac{1}{(2m+1)^2} \sum_{k=-m}^{m} \sum_{l=-m}^{m} X(x + k, y + l)$$

$$l_2(x, y) = \frac{1}{(2m+1)^2} \sum_{k=-m}^{m} \sum_{l=-m}^{m} \left[X(x + k, y + l) - l_1(x, y)\right]^2$$

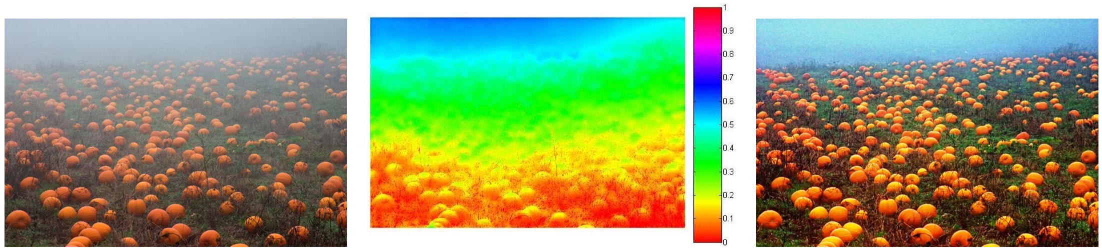
If mean contrast is denoted as

$$\bar{C}_I = \frac{1}{MN} \sum_{y=0}^{N-1} \sum_{x=0}^{M-1} C(x, y) \tag{14}$$

then Contrast gain (C_{gain}) is

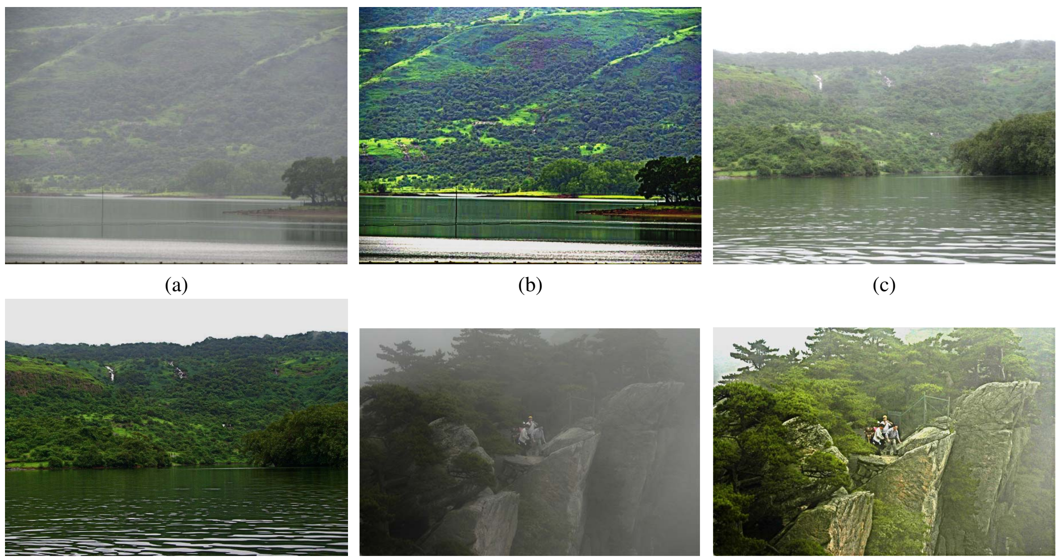
$$C_{gain} = \bar{C}_{I_{enh}} - \bar{C}_{I_{org}} \tag{15}$$

where, $\bar{C}_{I_{enh}}$ is mean contrast of enhanced image and $\bar{C}_{I_{org}}$ is mean contrast of original image. It is known that clear day images have more contrast than images plagued by fog. Hence contrast gain for all the existing fog removal algorithms should be positive. Moreover, stronger contrast gain indicates better enhancement of the image.



(a) (b) (c)

Fig. 3: (a) original foggy ‘pumpkins’ image, (b) corresponding airlight map using bilateral filter, and (c) image restored by proposed algorithm.



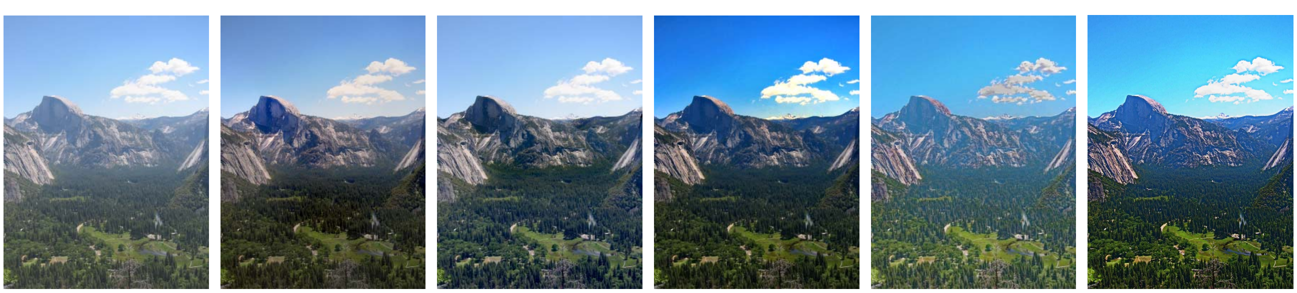
(a) (b) (c)

(d) (e) (f)

Fig. 4: (a) Original foggy ‘lonavala01’ image, (b) restored ‘lonavala01’ image, (c) original foggy ‘lonavala02’ image (d) restored ‘lonavala02’ image, (e) original foggy ‘yellow mountain’ image, (f) restored ‘yellow mountain’ image. These results are shown for proposed algorithm.

(a) (b) (c) (d) (e) (f)

Fig. 5: (a) Original foggy image ‘ny17’. Image restored by the algorithm (b) Fattal, (c) Kopf et al, (d) He et al, (e) Tarel et al, (f) Proposed.



(a) (b) (c) (d) (e) (f)

Fig. 6: (a) Original foggy image ‘y01’. Image restored by the algorithm (b) Fattal, (c) Kopf et al, (d) He et al, (e) Tarel et al, (f) Proposed.

(a) (b) (c) (d) (e) (f)

Fig. 7: (a) Original foggy image 'y16'. Image restored by the algorithm (b) Fattal, (c) Kopf et al, (d) He et al, (e) Tarel et al, (f) Proposed.

TABLE I: Contrast gain (C_{gain}) and percentage of saturated pixels (σ) produced by competing methods on three different images.

Image	Method									
	Fattal		Kopf et al		He et al		Tarel et al		Proposed	
	C_{gain}	σ	C_{gain}	σ	C_{gain}	σ	C_{gain}	σ	C_{gain}	σ
'ny17'	4.2680	2.0058	4.2770	1.3507	5.3181	0.2215	6.6197	0.0011	**11.6090**	**0.0001**
'y01'	1.2355	0.1155	2.3507	0.0194	2.2386	1.0084	1.6732	0.0011	**4.0698**	**0.0000**
'y16'	1.3072	0.3203	1.8411	0.2835	2.5165	0.1738	4.4303	0.0004	**9.4544**	**0.0003**

B. Number of saturated pixels

The contrast gain should not be so high that the pixels of the output image become saturated. Percentage of the saturated pixels [13] σ is denoted as

$$\sigma = \frac{n}{M \times N} \times 100 \tag{16}$$

where n is the number of pixels which are saturated (either completely black or white) after the restoration but were not before. Low value of σ indicates better performance of the algorithms.

IV. Simulation and Results

Simulation of proposed fog removal algorithm is carried out in various foggy images: 'pumpkins', 'lonavala01', 'lonavala02', 'yellow mountain', 'ny17', 'y01', 'y16'. All simulation have done in MATLAB 7.0.4 environment. For initialization of airlight map β is 0.9. In post processing step, values of r_1 and r_2 are set by the cumulative histogram of the input image. r_1 and r_2 are intensity values of the 10% and 90% of cumulative histogram respectively. Values of s_1 and s_2 are the 5% and 95% of output intensity range i.e. [0 255]. Here value of r_1, r_2, s_1 and s_2 depend upon the image histogram and thus according to the contrast of the image, their values are adjusted. Effect of this contrast stretching function is more on low contrast images and low on high contrast images. These parameters (r_1, r_2, s_1 and s_2) are data driven and avoids the needs of the user intervention. Use of histogram equalization as pre-processing step and histogram stretching as post-processing step is found to improve the quality of restoration for all the images in this experiment.

Airlight map estimation for real foggy image is shown in Fig.3b. However, airlight map is a gray image but for better visualization, it is shown in pseudo color. It is observed that, in foggy image estimated airlight map depends upon the distance of scene points from camera. Estimated airlight map is able to capture the discontinuities across the edges and smooth over the objects. Bilateral filter [11] performs smoothing of intra region. Results of the proposed algorithm is shown in Fig.3c.

Quantitative and qualitative performance of proposed algorithm is compared with other existing fog removal algorithms. Qualitative results of proposed algorithm are shown in Fig.4. Results show that proposed algorithm restores images with good perceptual quality. Results for the comparison of proposed algorithm with other existing algorithm are shown in Figs. 5, 6 and 7. Results show that proposed algorithm restores foggy images better than other existing algorithms. However, visually it is very difficult to find out the best algorithm. Hence there is a requirement of some quantitative analysis. Performance of fog removal algorithms is quantitatively analyzed in terms of C_{gain} and σ. C_{gain} and σ are measured over full resolution images. For simulation of contrast gain, 5×5 window ($m = 2$) is chosen. Quantitative results are shown in Table I. Results show that contrast gain (C_{gain}) for proposed algorithm is higher than other existing algorithms. Percentage of number of saturated pixels (σ) is very low for proposed algorithm. According to the average increase of contrast gain, these algorithms can be arranged in descending order as: Proposed, Tarel et al, He et al, Kopf et al, and Fattal. According to the average of the smallest σ, these algorithms can be arranged in descending order as: Proposed, Tarel et al, He et al, Kopf et al, and Fattal.

V. Conclusion

In this paper, a novel and efficient fog removal algorithm is proposed. Proposed algorithm uses bilateral filter to generate airlight map. Generated airlight map preserves edges and performs smoothing over the object region. Proposed algorithm does not require user intervention and can be applied for color and gray scale images. Results show that proposed algorithm enhances foggy image better than prior state of the art algorithms. Even in case of heavy fog, proposed algorithm performs well, as algorithm is independent of the density of fog present in the image. In order to evaluate the performance, contrast gain and percentage of number of saturated pixels are calculated. Results confirm that there is a significant improvement in the enhancement of foggy images. Proposed algorithm can be used as a pre processing step for various computer vision algorithms which use feature information such as object detection, tracking, segmentation and recognition.

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