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Modified Visibility Restoration-Based Contrast Enhancement Algorithm for Colour Foggy Images

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ABSTRACT
The visibility enhancement of colour foggy images is a very challenging task for many real-time applications. In this paper, we have proposed an efficient and robust algorithm for visibility enhancement of colour foggy images. The proposed algorithm works in two steps: in the first step, modified visibility restoration algorithm is applied for visibility enhancement, and in the second step, sigmoid-function-based contrast enhancement technique is applied for colour contrast enhancement of images. The quantitative and qualitative results of proposed and other state-of-the-art algorithms for colour foggy images are obtained in terms of fog aware density evaluator, fog reduction factor (FRF), measure of enhancement (EME), and measure of enhancement factor (EMF) on different colour foggy image databases. Results reveal the strength of proposed algorithm mathematically on the basis of fog thickness estimation from original image and output-enhanced image, FRF, EME, and EMF for colour foggy images. Experimental results shows that the proposed algorithm provides better quantitative and qualitative results as compared to other state-of-the-art algorithms for colour foggy images. Finally, the proposed algorithm is highly efficient for visibility enhancement of colour foggy images.

KEYWORDS
Contrast enhancement; Fog density; Fog reduction factor; Guided filter; Measure of enhancement; Visibility restoration

1. INTRODUCTION

Foggy or hazy environment provides a significant impact on the colour photos or images shot in such environment. Such type of photographic images contains lower visibility, low contrast, and faint in colour [1]. Due to the presence of foggy or hazy particle (size $>10^{-4}$ μm) [2], light reflected from the object is scattered and absorbed by such particles, so that the visibility of the scene is degraded causing the effect on colour images taken in this environment. Many enhancement algorithms are applied on these types of images so that contrast and colour visibility of the image are cleared for the viewers. Enhancement of the visibility of foggy degraded colour images is also useful in many applications like weather forecasting, analysis of satellite images, and advance driving assistance system for identifying lane marking and signal identification in bad weather images [3]. In this paper, we use a bilateral filter, basically a photometric weight into standard Gaussian filter named as guided bilateral filter, is used in different applications of images like enhancement and fog removal of the images [4]. To improve the visibility and contrast enhancement of colour foggy images, we have proposed a modified visibility restoration-based contrast enhancement (MVRCE) algorithm and evaluated the fog density and colour enhancement factor through fog aware density evaluator (FADE) model [5–7] and measure of enhancement factor [8].

The structure of this research paper is as follows: in Section 2, related work regarding visibility enhancement of foggy or hazy colour images is presented. Section 3 presents proposed modified algorithm for visibility enhancement of colour foggy images. Section 4 describes the related results and the discussion of coloured foggy images in terms of fog reduction factor (FRF), measure of enhancement (EME), and measure of enhancement factor (EMF). And finally, conclusion is drawn in Section 5.

2. RELATED WORK

In the field of visibility and contrast enhancement of colour images for various vision applications in real world, many authors proposed the algorithms during the last decade. In [9], He *et al.* proposed a dark channel prior (DCP) to remove haze from a single-input image. They estimate the thickness of the haze by using the concept of DCP, and obtain a good-quality haze-less image. They constrained an air–light assumption in this model [9] that is very influential on the image. In [10,11], Eduardo *et al.* and He *et al.* proposed a very effective algorithm for computer vision and computer graphics,

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and they used guided-based bilateral filter for smoothing and edge preserving in the degraded images. In [2], Narasimhan and Nayar proposed two scattering models to calculate the scene properties of the images under hazy or foggy conditions. They also visually analysed these models under different weather conditions. In [3], Tarel *et al.* proposed the algorithm for homogeneous as well as heterogeneous fog. They proposed the method to generate the synthetic hazy environment and deal with the enhancement technique using planner assumption (PA) and no-black-pixel constraint (NBPC) for visibility enhancement of degraded images. A comparative and quantitative study for various enhancement algorithms is also shown in this paper [3]. The authors proposed a matrix to compute the depth of resorted image by focusing the PA only. In [4], the authors proposed a joint/cross-guided bilateral filter, for edge-preserving and smoothing tools for degraded images in many applications. It can also handle the non-Gaussian noise on the image. The main limitation of this filter is to handle the editing of colouring and decolouring of the image.

In [5], Lark Kwon Choi *et al.* proposed an algorithm based on FADE for estimating the fog in degraded images. They developed a reference-less assessment-based defogger system (DEFADE). They also enlisted the fog aware statistical parameters and computed the prediction of fog density in the foggy image as well as de-foggy images. The limitation of this DEFADE algorithm was that it required all statistical features defined in the perceptual fog density. In [12], Ancuti *et al.* proposed a technique for single hazy images. They applied a white balance and contrast enhancement procedure by taking two hazy inputs in fusion-based algorithm. The only consideration to obtain a defoggy or dehazy image chooses the appropriate weight map in fusion-based technique. In [13], Meng *et al.* proposed a model that is based on weighted L_1 normalization for calculating the transmission of scene in foggy images. Author also described for scene transmission and scene geometry of the image for estimation the colour depth to avoid the depth ambiguity in foggy images.

In [14], Yu Li *et al.* drew the attention on night-time hazy images within the presence of street light or vehicle light. They proposed a model by adding a glow term in Koschmieder equation [3]. By reducing the glow term in night-time hazy images, rest of the procedure treated same as day-time hazy images, means focus only intrinsic luminous and sky luminous [3]. They took a rough approximation for atmospheric light and treated it as a locally constant in the model. In [15], Li Xu *et al.* proposed an algorithm based on L_0 gradient minimization for sharpening the edges and smoothing the colour image. Such an algorithm method implies for the image editing by non-zero gradient control for the prominent structure in control manner. In some cases, over-sharpening and smoothing results remove the original texture in the output image. In [16], Quingsong *et al.* enhanced the hazy or foggy images through the scene depth estimation of input images. They proposed a linear type of mathematical model to estimate the transmission through scene radiance by atmospheric scattering model. This model is a single-haze-image-based constant atmosphere scattering (β) assumption model.

In [17], Narasimhan *et al.* proposed an algorithm for the depth discontinuities for the change in the intensity of scene points in the image under different weather conditions. Restore the contrast is the key feature of the algorithm. This algorithm is computationally fast. This mathematics model [17] is only for monochrome image under homogeneous foggy or hazy environment. In [18], Hautiere *et al.* described the region of interest in the degraded image for the segmentation and compute the fog density in horizontal line for driving system in flat areas and only in front of the vehicle-free space area. This algorithm [18] provides better enhancement of foggy images under flat region.

In [19], Tarel's *et al.* proposed a visibility restoration technique for the enhancement of foggy images. This algorithm is the fastest among the previous algorithms. When the depth information is not available, it is not possible to apply Koschmieder law [3] directly on foggy images; so this technique [19] is suitable under these conditions. This fastest algorithm is used for obstacle detection, lane marking, etc. The complexity of this algorithm depends on the size of the image, which means the number of the pixels of the image only. In [20], the authors have proposed an efficient contrast enhancement technique and they applied the proposed technique to improve the visual representation of computed tomography medical images. This algorithm employs an easy, fast, and reliable method to improve the contrast of different types of colour images because it is directly applied to the entire image.

In [21], the authors developed a two-step method for contrast enhancement of natural colour images. In this paper, the authors have not applied the proposed algorithm for foggy images. In [22], Tan proposed a cost function in the framework of Markov random field (MRF). The author used a single-haze image to obtain an optical model by calculating the chromaticity and white atmospheric light for the cost function. Cost function mainly depends on air–light variation from the distance of the objects to the viewer. This technique is applied in various fields of image enhancement. The limitation of this technique is the presence of halo effect in the depth discontinuities of the image. In [23], S. Lee *et al.* presented a detailed review on DCP-based image dehazing algorithms. In this paper, the authors mainly described the removal of haze under the physical degradation model. They focused on mainly four steps: atmospheric light estimation, transmission map estimation, transmission map refinement, and image reconstruction. This four-step dehazing process makes it possible to provide a step-by-step approach to the complex solution of the ill-posed inverse problem. In [24], F. Hussain *et al.* proposed a novel approach for camera-based advanced driver assistance systems using deep neural network. In this paper, the authors have used deep neural network for mathematical modelling of fog in an image. But the authors have not evaluated quantitative performance metric such as fog density and measure of enhancement. In order to improve the visibility enhancement of images under foggy bad weather condition, a MVRCE algorithm is proposed in this paper.

In [25], the authors explained dark channel phenomenon through optical model. They applied atmospheric scattering parameter and joint bilateral filter on their model for removing the haze in fast speed from hazy images. In [26], the authors estimated the transmission map of hazy image by edge-preserving decomposition techniques. For improving the enhancement, the author proposed a guided image filter to decompose the image in base layer and detail layer from dark channel of haze image. In [27,28], the authors proposed a novel and effective approach to remove the haze problems encountered by local light sources and colour shifting. In this paper, the authors used DCP for local light source problems and colour analysis (CA) module for colour shifting. Finally, a visibility restoration technique is applied for removing the haze or fog from hazy degraded images. Such techniques are effectively applied on traffic surveillance system. In [29], the authors proposed Laplacian-based visibility restoration to solve the haze thickness estimation and colour cost problems. The algorithm is good for the image captured during the sand storm conditions. In [30], the authors proposed a multi-scale depth fusion method for defog of single foggy images. This fusion technique is based on spatial Markov dependence which is formulated on energy minimization problems. For smoothing and edge preserving of foggy images author proposed a Laplacian–Markov random field method in multi scale fusion technique. In [31], the authors proposed a method for single-image haze removal using adaptive dark channel and post enhancement. First, an associative filter and adaptive dark channel is efficiently applied to a single hazy image, then an enhancement technique is applied to restore haze and oversaturation free image.

In [32], the authors proposed an algorithm for minimizing the halo effect in dehazy images. They proposed quad-tree decomposition for the estimation of air–light and Robinson–Laplacian operator for edge detection in the hazy images. In [33], the authors proposed a neural-network-based dehaze net to analyse the layer formation for image dehazing. After that, bilateral filtering is applied to improve the quality of image. In [34], the authors proposed an edge-collapse-based dehazing algorithm for the estimation of the transmission map. In [35], the authors implemented a high-speed gain intervention refinement filter with DCP for haze removal of hazy images. This technique also concerns to minimize the halo effect. In [36], the authors described the techniques to estimate the air–light in the presence of other external sources. In [37], the authors described visibility restoration approach based on bi-histogram modification techniques which estimate and calculate the haze density in transmission map. In [38], the authors proposed DCP-based fisher's linear discriminate for hazy images. In [39], the author described a modified histogram technique for contrast enhancement of hazy images. They improved the contrast of image through gamma correction and probability distribution of pixels. In [40], the authors described a Bezier-curve-based fast-modified histogram technique for the contrast enhancement of video and images.

3. PROPOSED ALGORITHM

In this section, we have described proposed MVRCE algorithm in detail. The proposed algorithm is described in two phases: in the first phase, modified visibility restoration algorithm is applied, and in the second phase, sigmoid-based contrast enhancement technique is applied on the output image of the first phase. The proposed modified visibility restoration-based contrast enhancement is abbreviated as MVRCE. The model of proposed MVRCE algorithm is shown in Figure 1.

The proposed MVRCE algorithm is explained as follows:

3.1 Modified Visibility Restoration Algorithm

Appearance of image depends on conditions influenced by bad weather conditions like hazy, rain, snow, smoke and fog, etc. The model of foggy images is designed by

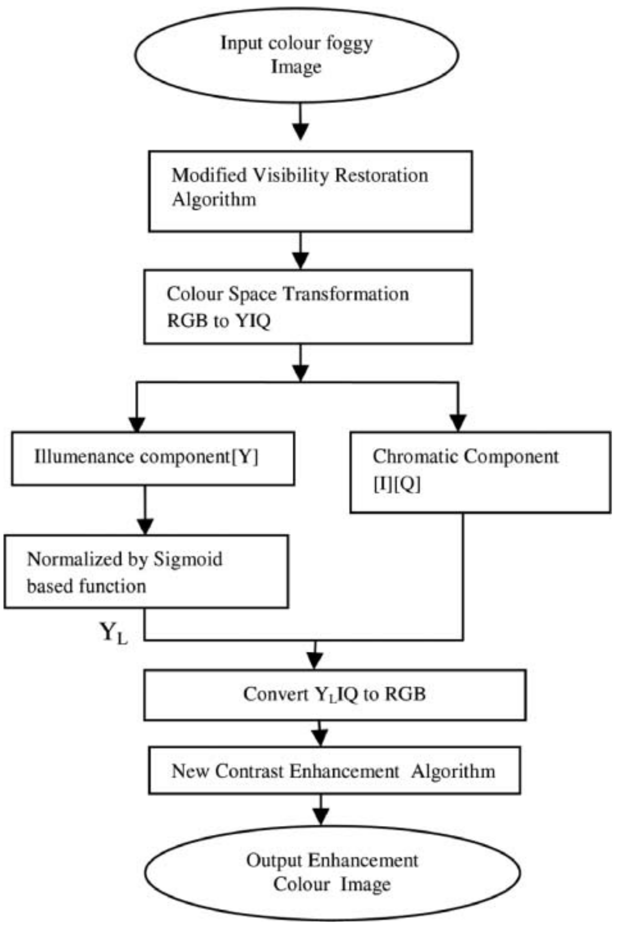

Figure 1: Block diagram of proposed MVRCE algorithm

Koschmieder [3], which is given as follows:

$$G(x,y) = G_0(x,y)e^{-\beta L(x,y)} + G_s(1 - e^{-\beta L(x,y)}) \tag{1}$$

where $G(x, y)$ is apparent luminance of pixel (x, y) at a distance of $L(x, y)$, $G_0(x, y)$ is intrinsic luminance and G_s is sky luminance value, and β is an extinction coefficient for atmosphere. This grey level model is also extended for colour images for each R, G, B components separately.

Visibility restoration demands the estimation of real colour of images $G_0(x, y)$ and other foggy properties like β, G_s, and depth scene $L(x, y)$. If the scene depth is not known, then it is very difficult to separate between β and L as described in Equation (1); therefore, the computed intensity of atmospheric veil [19] is defined as

$$I(x,y) = G_s(1 - e^{-\beta L(x,y)}) \Rightarrow e^{-\beta L(x,y)} = \left(1 - \frac{I(x,y)}{G_s}\right) \tag{2}$$

Now substituting the value of $e^{-\beta L(x,y)}$ in Equation (1),

$$G(x,y) = V(x,y)\left(1 - \frac{I(x,y)}{G_s}\right) + I(x,y) \tag{3}$$

Now let us consider $I(x, y)$ as the observed image intensity for greyscale and colour images at pixel (x, y) and $V(x, y)$ is the defoggy image intensity.

The defoggy image intensity is derived from Equation (3) as

$$V(x,y) = \frac{G(x,y) - I(x,y)}{\left(1 - \frac{I(x,y)}{G_s}\right)} \tag{4}$$

For the visibility restoration of images, the atmospheric veil $I(x, y)$ is analysed. The first assumption is that when observed foggy image is known, that means $I(x, y) \geq 0$ and pure white, it is not exceeded from $G(x, y)$. To compute image $T(x, y)$ = minimum of $G(x, y)$ for each pixel in RGB, where $T(x, y)$ is a foggy image in the observed image $G(x, y)$, for greyscale image $T(x, y) = G(x, y)$ and for colour image process R, G, B component separately. In the second assumption, that is. $I(x, y) \leq T(x, y)$, the problem is formalized as the optimized maximum of $I(x,y)$ [19].

In order to perform edge preserving and smoothing, we have used fast-guided bilateral filter [4]. The intensity of atmospheric veil is obtained by

$$I(x,y) = \max(\min(nY(x,y), T(x,y)), 0) \tag{5}$$

where n is the control parameter for visibility strength and the value lies between 0 and 1, whereas the local average of T(x, y) is given as

$$X(x,y) = \underset{S_P}{\text{Guided}}(T(x,y)),$$

where S_P is the size of disc window that is applied in fast-guided bilateral filter.

The contrast in the texture which is not foggy is $\text{Guided}_{S_P}\ |T(x,y) - X(x,y)|$, and $Y(x,y) = X(x,y) - \text{Guided}_{S_P}(|T(x,y) - X(x,y)|)$. In the proposed MVRCE algorithm, we have chosen the value of $n = 0.9$ and $S_p = 64$, and both these parameters control the visibility restoration. The guided bilateral filter was proposed by Laurent Caraffa *et al.* [4] for visibility restoration algorithm for edge preserving and smoothing of image. The output weighted image of the guided filter is

$$f_{k+1}(x,y)=\frac{\sum_{t\in s_p} m_t\Phi((f_k(x,y)-G((x,y)+t))^2)G((x,y)+t)}{\sum_{t\in s_p} m_t\Phi((f_k(x,y)-G((x,y)+t))^2)}$$
$$m_t=w_s(\|t\|)w_g(G(x,y)-G((x,y)+t)) \tag{6}$$

where w_g is a photometric weight factor of spatial weight (w_s), $G(x,y)$ is the original input image, $f_k(x, y)$ is output of the guided filter, S_p is a square window $[-P, P] \times [-P, P]$ and ϕ is characterize noise model, adequately chosen with respect to image noise and converge towards a local minimum. Guided bilateral filter is flexible to its three weight, $w_s = 1$ for good quality guided filter.

3.2 New Contrast Enhancement Algorithm

In contrast enhancement algorithm, firstly the image is converted into *YIQ* colour space, that is used in NTSC and PAL formats of TV, where parameter *Y* (luminance) is used in both coloured and greyscale images, and *I* (hue) and *Q* (saturation) parameters are used in coloured image. Transformation from RGB to YIQ [21] is given as follows:

$$\left.\begin{aligned} Y&=0.299R+0.587G+0.114B\\ I&=0.596R-0.275G-0.321B\\ Q&=0.212R-0.523G-0.311B \end{aligned}\right\} \tag{7}$$

After colour space transformation, the *Y* component is normalized as follows:

$$f_k(x,y)=Y=0.299R+0.587G+0.114B \tag{8}$$

Normalized Intensity is given by

$$f_k{'}(x,y)=\frac{f_k(x,y)}{255} \tag{9}$$

Lightness component is transform by the sigmoid function

$$S_n(x,y)=\frac{1}{\left(1+\sqrt{\frac{(1-f_k'(x,y))}{f_k'(x,y)}}\right)} \tag{10}$$

Lightness component is denoted as Y_L, Converted RGB image is as follows:

$$\left.\begin{aligned} R&=Y_L+0.9563I+0.6210Q\\ G&=Y_L-0.2721I-0.6474Q\\ B&=Y_L-1.1070I+1.7046Q \end{aligned}\right\} \tag{11}$$

Now the output RGB image is considered as $f(x,y)$. The contrast enhancement technique [20] is utilized in spatial domain and applied directly to entire image $f(x,y)$ in place of pixel by pixel. The image is normalized based on the size of the image:

$$\text{Enhancement parameter } \gamma=\frac{\sum_{x=1}^{N}\sum_{y=1}^{N} f(x,y)}{N\times N} \tag{12}$$

In Equation (12), enhancement parameter (γ) is calculated by the sum of all pixel values divided by its image size (N x N). Finally, the contrast of image is enhanced by CE, which is given as follows:

$$\mathrm{CE}=\frac{[f(x,y)-\min(f(x,y))]\times e^{\gamma}}{[\max(f(x,y))-\min(f(x,y))]} \tag{13}$$

where min($f(x,y)$) and max($f(x,y)$) are the minimum and maximum pixel values of degraded image, γ is the enhancement parameter, and CE is the contrast-enhanced image.

4. RESULTS AND DISCUSSION

In this section, we have presented the analysis of quantitative and qualitative results of the proposed MVRCE algorithm. We have also discussed the simulation results of proposed MVRCE algorithm and state-of-the-art algorithms on different colour foggy image databases [5,19]. In order to compute the results of the proposed MVRCE algorithm and other state-of-the-art algorithms, they are implemented on 64-bit system with Core i3 processor, 4GB RAM and MATLAB [release 2015a] software.

4.1 Image Databases

The simulation results of the proposed MVRCE algorithm and other state-of-the-art algorithms are obtained on standard test foggy images which are taken from the Tarel's foggy image database [19] (http://perso.lcpc.fr/tarel.jean-philippe), Lark Kwon Choi's foggy image database [5] (http://live.ece.utexas.edu/research/fog/index.html), and other image data-sets.

4.2 Quality Performance Metrics

In order to evaluate the performance parameters of the proposed MVRCE algorithm and other state-of-the-art algorithms, we have tested these algorithms on different standard test foggy images [5,19]. Image quality parameters have been evaluated on eight different foggy images (*i.e.* 9.png (512 × 512), 28.jpg (512 × 512), Train.bmp (512 × 512), y11_photo.png (512 × 512), IMG_8763.jpg (512 × 512), 40.jpg (512 × 512), 41.jpg (512 × 512), Cones.jpg (512 × 512)] from the database [5,19]. In order to analyse the quality of output defoggy image, the important parameter is FRF which is defined in Equation (14). FADE for calculating the fog in an image [5,10] based on natural scene statistics like local mean [7], local coefficient of variance for sharpness [41], contrast energy [42], and image entropy [5,43] and pixelwise DCP [9,44,45] colour saturation and colourfulness matrix [46]. To find the fog density, there are 12 features calculated [5] in a squared n x n image. The numerical value of FRF is defined as the difference between the fog densities of input colour foggy image (D_f) and the output de-foggy colour image (D_{df}):

$$\text{FRF} = D_f - D_{df} \tag{14}$$

Lower the value of fog density in the defoggy image, higher the value of FRF; this parameter implies that the quality of algorithm as well as the enhanced colour defoggy image. The D_f, D_{df}, and FRF metric values of the proposed MVRCE algorithm and other state-of-the-art algorithms like Trael's [19], Qingsong's [16], Ancuti's [12], He & Sun's [10], Meng & Wang's [13],Yu-ei's [14], and Choi's's [5] are evaluated and given in Tables 1–8. The second quality parameter to analyse the quality of the colour defoggy image is the EMF [47,48]. EMF is defined as the ratio of EME of output colour defoggy image to EME of input colour foggy image. The expression of EME and EMF is given in Equations (15) and (16), respectively [47]. The EME and EMF image quality metrics of the proposed MVRCE algorithm and other

Table 1: Performance comparison of various visibility enhancement algorithms for foggy image (9.png, 512 × 512)

	Fog density (D) and Fog reduction factor (FRF) parameters			Measurement of enhancement (EME) and EMF parameters		
Algorithm	D_f of foggy image	D_{df} of defoggy image	FRF value	EME of foggy image	EME of defoggy image	EMF value
Tarel's [19]	2.3573	1.6573	0.7000	12.4309	20.7752	1.6713
Qingsong's [16]	2.3573	1.5059	0.8514	12.4309	13.8494	1.1141
Ancuti's [12]	2.3573	1.4939	0.8637	12.4309	15.9324	1.2817
He & Sun's [10]	2.3573	2.1585	0.1988	12.4309	16.7866	1.3504
Meng &Wang's [13]	2.3573	1.2515	1.1058	12.4309	21.4637	1.7411
Yu-li's [14]	2.3573	1.4477	0.9157	12.4309	13.8064	1.1106
Choi's [5]	2.3573	1.1699	1.1874	12.4309	12.5465	1.0093
Proposed MVRCE algorithm	**2.3573**	**1.0473**	**1.3101**	**12.4309**	**20.8356**	**1.6761**

Table 2: Performance comparison of various visibility enhancement algorithms for foggy image (28.jpg, 512 × 512)

	Fog density (D) and fog reduction factor (FRF) parameters			Measurement of enhancement (EME) and EMF parameters		
Algorithm	D_f of foggy image	D_{df} of defoggy image	FRF value	EME of foggy image	EME of defoggy image	EMF value
Tarel's [19]	5.4907	3.7128	1.7779	3.8459	9.0558	2.3547
Qingsong's [16]	5.4907	3.0563	2.4345	3.8459	6.4721	1.6829
Ancuti's [12]	5.4907	1.7102	3.7805	3.8459	9.4489	2.4569
He & Sun's [10]	5.4907	4.0504	1.4403	3.8459	8.9078	2.3162
Meng &Wang's [13]	5.4907	2.1381	3.3526	3.8459	13.7048	3.5635
Yu-li's [14]	5.4907	1.4657	4.0250	3.8459	11.2446	2.9238
Choi's [5]	5.4907	1.6982	3.7925	3.8459	4.0607	1.0559
Proposed MVRCE algorithm	**5.4907**	**1.6616**	**3.8291**	**3.8459**	**17.4572**	**4.5392**

Table 3: Performance comparison of various visibility enhancement algorithms for foggy image (y11_photo.png, 512 × 512)

	Fog density (D) and fog reduction factor (FRF) parameters			Measurement of enhancement (EME) and EMF parameters		
Algorithm	D_f of foggy image	D_{df} of defoggy image	FRF value	EME of foggy image	EME of defoggy image	EMF value
Tarel's [19]	3.5984	2.4315	1.1669	7.6244	11.4169	1.4974
Qingsong's [16]	3.5984	1.6442	1.9542	7.6244	11.6437	1.5272
Ancuti's [12]	3.5984	1.6070	1.9914	7.6244	11.2399	1.4743
He & Sun's [10]	3.5984	3.0972	0.5012	7.6244	13.6476	1.7900
Meng &Wang's [13]	3.5984	1.8793	1.7191	7.6244	15.3592	2.0145
Yu-li's [14]	3.5984	1.2116	2.4768	7.6244	17.0777	2.2399
Choi's [5]	3.5984	1.4638	2.1346	7.6244	10.2818	1.3485
Proposed MVRCE algorithm	**3.5984**	**1.1866**	**2.4118**	**7.6244**	**21.2754**	**2.7904**

Table 4: Performance comparison of various visibility enhancement algorithms for foggy image (IMG_8763.jpg)

	Fog density (*D*) and fog reduction factor (FRF) parameters			Measurement of enhancement (EME) and EMF parameters		
Algorithm	D_f of foggy image	D_{df} of defoggy image	FRF value	EME of foggy image	EME of defoggy image	EMF value
Tarel's [19]	4.4981	3.1147	1.3834	9.3312	17.5204	1.8776
Qingsong's [16]	4.4981	2.2829	2.2152	9.3312	12.8375	1.3758
Ancuti's [12]	4.4981	1.3887	3.1094	9.3312	15.3502	1.0450
He & Sun's [10]	4.4981	3.7724	0.7256	9.3312	15.8800	1.7018
Meng &Wang's [13]	4.4981	1.5440	2.9540	9.3312	21.7579	2.3317
Yu-li's [14]	4.4981	1.3197	3.1783	9.3312	13.5644	1.4537
Choi's [5]	4.4981	1.2240	3.2741	9.3312	8.4878	0.9096
Proposed MVRCE algorithm	**4.4981**	**1.1824**	**3.3156**	**9.3312**	**28.0707**	**3.083**

Table 5: Performance comparison of various visibility enhancement algorithms for foggy image (Cones.jpg, 512 × 512)

	Fog density (*D*) and fog reduction factor (FRF) parameters			Measurement of enhancement (EME) and EMF parameters		
Algorithm	D_f of foggy image	D_{df} of defoggy image	FRF value	EME of foggy image	EME of defoggy image	EMF value
Tarel's [19]	3.7757	2.3486	1.4271	8.7478	16.3636	1.8706
Qingsong's [16]	3.7757	2.1989	1.5768	8.7478	10.9547	1.2523
Ancuti's [12]	3.7757	2.1207	1.6550	8.7478	14.3092	1.6357
He & Sun's [10]	3.7757	3.1277	0.6480	8.7478	18.9639	2.1678
Meng &Wang's [13]	3.7757	1.6580	2.1177	8.7478	19.0601	2.1788
Yu-li's [14]	3.7757	1.4690	2.3067	8.7478	15.6770	1.7921
Choi's [5]	3.7757	1.6971	2.0786	8.7478	20.4249	2.3348
Proposed MVRCE Algorithm	**3.7757**	**1.1237**	**2.6520**	**8.7478**	**27.7438**	**3.1715**

Table 6: Performance comparison of various visibility enhancement algorithms for foggy image (Train.bmp, 512×512)

	Fog density (*D*) and fog reduction factor (FRF) parameters			Measurement of enhancement (EME) and EMF parameters		
Algorithm	D_f of foggy image	D_{df} of defoggy image	FRF value	EME of foggy image	EME of defoggy image	EMF value
Tarel's [19]	4.4870	3.4784	1.0086	5.4335	10.0893	1.8569
Qingsong's [16]	4.4870	2.1925	2.2945	5.4335	13.5217	2.4886
Ancuti's [12]	4.4870	1.9956	2.4915	5.4335	12.1924	2.2439
He & Sun's [10]	4.4870	3.6258	0.8613	5.4335	10.4706	1.9270
Meng &Wang's [13]	4.4870	1.5403	2.9465	5.4335	20.4711	3.7676
Yu-li's [14]	4.4870	1.2166	3.2704	5.4335	17.5244	3.2253
Choi's [5]	4.4870	1.6783	2.8088	5.4335	10.6881	1.9671
Proposed MVRCE algorithm	**4.4870**	**1.2882**	**3.1989**	**5.4335**	**21.6460**	**3.9838**

Table 7: Performance comparison of various visibility enhancement algorithms for foggy image (40.jpg, 512 × 512)

	Fog density (*D*) and fog reduction factor (FRF) parameters			Measurement of enhancement (EME) and EMF parameters		
Algorithm	D_f of foggy image	D_{df} of defoggy image	FRF value	EME of foggy image	EME of defoggy image	EMF value
Tarel's [19]	3.9894	3.1145	0.8749	8.7462	15.2515	1.7438
Qingsong's [16]	3.9894	1.8342	2.1552	8.7462	16.9894	1.9425
Ancuti's [12]	3.9894	1.2855	2.7039	8.7462	17.7962	2.0347
He & Sun's [10]	3.9894	3.5321	0.4573	8.7462	13.4265	1.5351
Meng &Wang's [13]	3.9894	1.6101	2.3793	8.7462	22.9206	2.6206
Yu-li's [14]	3.9894	1.2396	2.7498	8.7462	17.2599	1.9734
Choi's [5]	3.9894	1.9038	2.0856	8.7462	20.4051	2.3330
Proposed MVRCE algorithm	**3.9894**	**1.3540**	**2.6354**	**8.7462**	**25.4504**	**2.9099**

Table 8: Performance comparison of various visibility enhancement algorithms for foggy image (41.jpg, 512 × 512)

	Fog density (*D*) and fog reduction factor (FRF) parameters			Measurement of enhancement (EME) and EMF parameters		
Algorithm	D_f of foggy image	D_{df} of defoggy image	FRF value	EME of foggy image	EME of defoggy image	EMF value
Tarel's [19]	5.0023	3.8469	1.1553	4.2150	9.1124	2.1619
Qingsong's [16]	5.0023	2.5394	2.4628	4.2150	9.8979	2.3483
Ancuti's [12]	5.0023	2.4098	2.5925	4.2150	11.0766	2.6279
He & Sun's [10]	5.0023	3.7921	1.2101	4.2150	9.9975	2.3719
Meng &Wang's [13]	5.0023	1.9388	3.0635	4.2150	15.5177	3.6816
Yu-li's [14]	5.0023	1.7141	3.2882	4.2150	12.9041	3.0615
Choi's [5]	5.0023	3.7937	1.2086	4.2150	11.3720	2.6980
Proposed MVRCE algorithm	**5.0023**	**1.3659**	**3.6364**	**4.2150**	**21.1761**	**5.0240**

state-of-the-art algorithms are evaluated and given in Tables 1–8. The EME [8,47,48] of image $f(x, y)$ with a one-dimensional $N_1 \times N_2$ pixels is given as follows:

$$\underset{k_1,k_2}{\mathrm{EME}} = \frac{1}{k_1 k_2}\sum_{l=1}^{k_1}\sum_{k=1}^{k_2}\left[20*\ln\left(\frac{f_{\max,k,l}}{f_{\min,k,l}}\right)\right] \tag{15}$$

where an image (f) is divided into $k_1 \times k_2$ blocks, $f_{\max,k,l}$ and $f_{\min,k,l}$ are the maximum and minimum values of the fth pixels in each block [47,48].

The EMF between output image and input image is defined as [8,47,48]

$$\mathrm{EMF} = \frac{\mathrm{EME}_{\text{output image} f(x,y)}}{\mathrm{EME}_{\text{input image} G(x,y)}} \tag{16}$$

4.3 Visual Enhancement Results

In this section, visual enhancement results of the proposed MVRCE algorithm and other state-of-the-art algorithms are evaluated and compared on different standard test colour foggy image databases. In this paper, we have presented the visual enhancement results of eight different colour foggy images (*i.e.* 9.png (512 × 512), 28.jpg (512 × 512), 40.jpg (512 × 512, Train.bmp (512 × 512), 41.jpg (512 × 512), Cones.jpg (512 × 512), y11_photo.png (512 × 512), IMG_8763.jpg (512 × 512). The visual enhancement results of the proposed MVRCE algorithm and other state-of-the-art algorithms are given in Figures 2 and 3. The visualization results of the proposed MVRCE algorithm in different colour defoggy images are given in Figure 4.

4.4 Discussions

The performance of the proposed MVRCE and other state-of-the-art algorithms is tested on different coloured foggy images from the databases [5,19], but here we have described the quantitative results of only eight standard colour foggy images from databases [5,19]. We have applied the proposed MVRCE and other state-of-the-art algorithms like Tarel's [19], Qingsong's [16], Ancuti's [12], He & Sun's [10], Meng & Wang's [13], Choi's [5] and Yu-li's [14] algorithms on these colour foggy images. The performance is compared in terms of numerical fog density value (D) in the original image as well as the defoggy image and FRF. We have presented the numerical value of fog density (D) and FRF for different visibility enhancement algorithms on images (Figures 2 and 3) in Tables 1–8, respectively. Here on the basis of the observation from Tables 1–8, the proposed MVRCE algorithm provided the better value of FRF among all other state-of-the-art algorithms.

In addition, the second colour image quality parameters are also measured in terms of EMF and EMF. We have calculated the numerical value of EME original image and output defoggy image for the proposed MVRCE and other state-of-the-art algorithms on eight different colour foggy images. All the numerical values of EME and EMF for the proposed MVRCE and other state-of-the-art algorithms are given in Tables 1–8. It can be observed from Tables 1–8 that the proposed MVRCE algorithm provided better output EME and better EMF value as compared to other state-of-the-art algorithms.

Finally, we have also observed from Figures 2–4 that the proposed MVRCE algorithm provided better visualization results as compared with other state-of-the-art algorithms. Visual comparative analysis of some images like 40.jpg, 41.jpg, Train.bmp, 28.jpg, 9.png, and y11_photo.png is given in Figure 4. It is observed from Figure 4 that in 40.jpg, building number and lane marking are clearly visible in comparison to other state-of-the-art algorithms. In 41.jpg, pole marking and object identification near the wall are clearly visible in comparison to other state-of-the-art algorithms. In image Train.bmp, all the signals and line crossing joint visibility are far better than other state-of-the-art algorithms. In image 28.jpg, building name and signalling arrow are clearly visible after applying the proposed MVRCE algorithm under foggy condition. In image 9.png and y11_photo.png, object identification and boundary detection are easily accessible after applying the proposed MVRCE algorithm. There are some halo effect problems in 9.png and 28.jpg, but visualization of all the images of the proposed MVRCE algorithm is better than all other algorithms. Hence, finally, we can state that under all observations like fog density (D_{df}), FRF, EMF, and EME, visualization results of our proposed MVRCE algorithm provided better visibility restoration results as compared to other state-of-the-art algorithms.

To check the superiority of our MVRCE algorithm in terms of speed or we can say the comparison of the processing time in terms of second, we compare the process time with the latest Tarel's [19], Meng & Weng [13], and Choi's [5] algorithms. We can observe from Table 9 that our proposed MVRCE algorithm takes much less processing time in comparison to the latest DEFADE Choi's algorithm [5]. The MVRCE algorithm is also faster than Tarel's [19] and Meng & Weng's [13] algorithms.

Figure 2: Defoggy results of various algorithms for different images

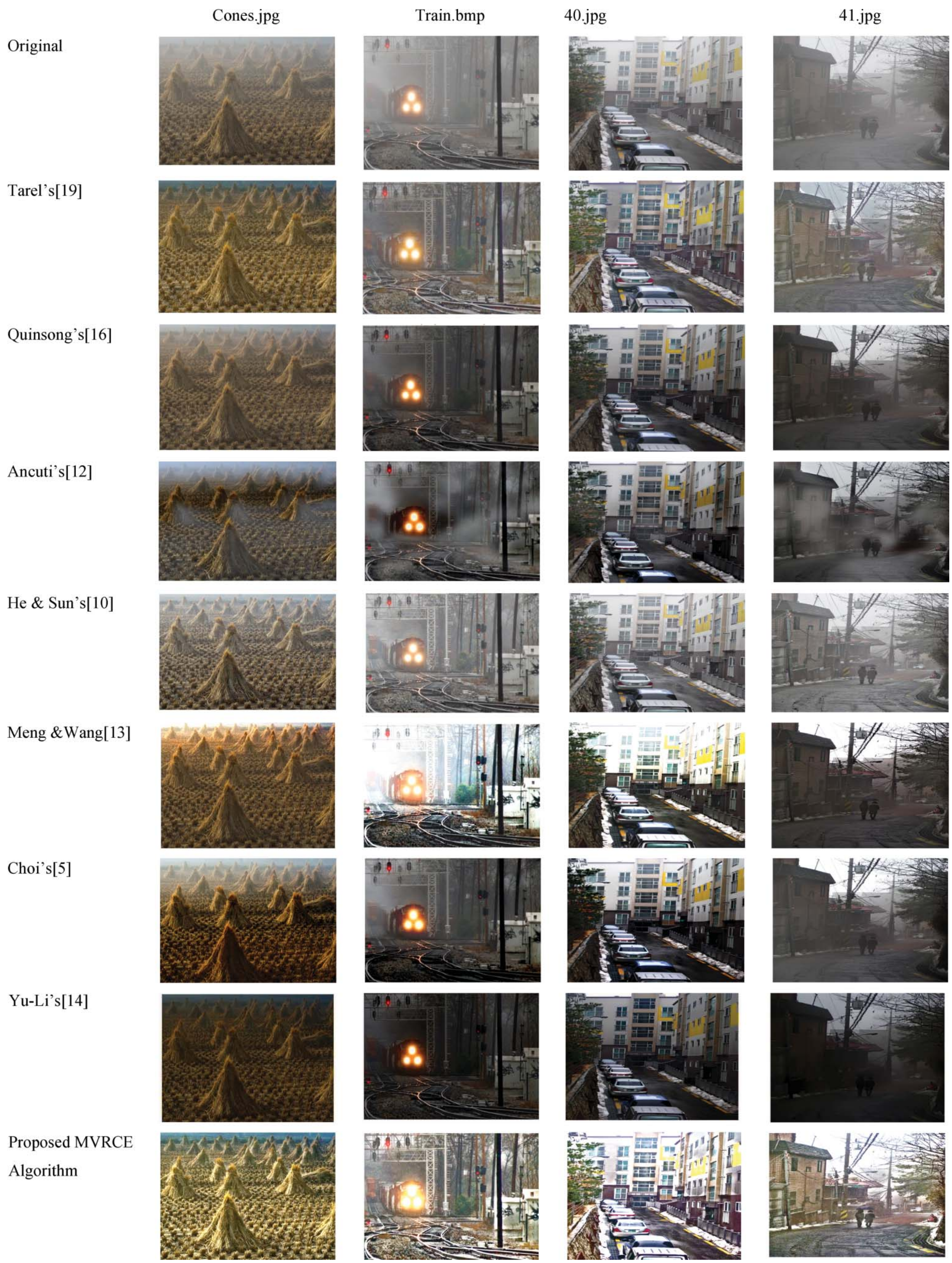

Figure 3: Defoggy results of various algorithms for different images

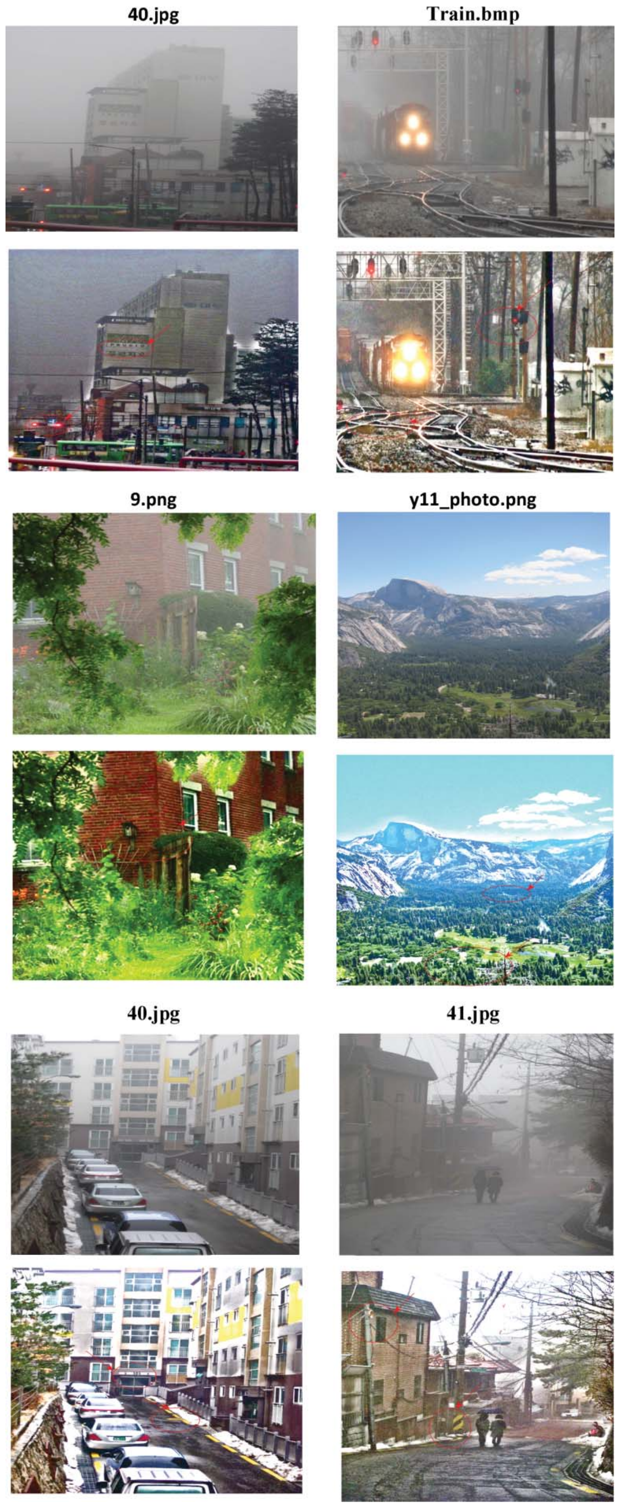

Figure 4: Visualization of proposed MVRCE algorithm in different images

The proposed MVRCE algorithm can be used for outdoor scene recognition and other applications. The proposed algorithm is helpful for object recognition and tracking under foggy weather condition. This will also be useful for traffic surveillance and person monitoring at airport.

5. CONCLUSION

This paper demonstrated robustness and effectiveness of the proposed MVRCE algorithm for visibility enhancement of coloured foggy images. The proposed MVRCE algorithm was tested on different colour foggy images from different foggy image databases. Qualitywise visibility restoration performance of the proposed MVRCE algorithm was evaluated and compared with other state-of-the-art algorithms. The performance of the proposed MVRCE algorithm was evaluated and compared in terms of fog density (D_{df}) and FRF with other existing algorithms. Results indicated that the proposed MVRCE algorithm has given the highest values of D_{df} and FRF in comparison with other state-of-the-art algorithms. Another parameter which we have analysed is the quality of image in terms of EME and EMF. Again, the results revealed that the proposed MVRCE algorithm was provided the best results as compared with other existing algorithms in terms of EME and EMF. Visualization of the defoggy images of our proposed MVRCE algorithm is also better as compared to other state-of-the-art algorithms. The processing time of the proposed MVRCE algorithm was less as compared to the latest DEFADE algorithm and some other state-of-the-art algorithms. Therefore, the proposed MVRCE algorithm performed very effectively and efficiently for the visibility of foggy-based degraded images.

The advantages of our MVRCE algorithm were as follows: (1) it is based on minimal input, *i.e.* a single image exhibiting robustness for various unseen images data, and (2) reduced complexity. We can also apply our MVRCE algorithm in many other degraded images such as in the fields of weather-degraded hazy images, satellite images for predictions of weather, and remote areas. This algorithm is also useful for traffic surveillance by improving the speed of MVRCE algorithm.

Table 9: Processing time (in second) comparison of proposed MVRCE algorithm with latest other's algorithm

Methods	9.png	28.jpg	y11_photo.png	IMG_8763.jpg	Train.bmp	Cones.jpg	40.jpg	41.jpg
Tarel's [19]	11.985	10.894	11.345	12.045	11.485	12.101	11.029	12.259
Meng & Wang's [13]	15.000	16.594	16.063	15.388	17.096	18.101	15.157	14.984
Choi's [5]	33.521	31.699	31.077	32.545	33.633	32.912	63.198	40.329
Proposed MVRCE algorithm	**11.500**	**10.817**	**11.339**	**10.821**	**11.347**	**11.696**	**10.258**	**11.463**

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