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A new image enhancement method considering both dynamic range and color constancy

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Abstract. This paper proposes an approach to improving color images suffering from low dynamic range by employing both histogram matching and histogram stretching techniques. In the first stage, the color image was transformed from RGB into HSV color space, in which the color information was separated from intensity. Then, an appropriate reference image was selected by comparing component V of the enhanced image with component V of the database images using a similarity measure. The selected image was used as the target image in histogram matching algorithm for enhancement. In the second stage, components V and S were linearly stretched in order to recover the image color information. Finally, using the treated V and S components and untreated component of H, the enhanced image was obtained in RGB color space by inverse transform. The qualitative and quantitative results showed that the contrast and color of the resultant image were greatly improved using the proposed method, which outperformed the current state-of-the-art methods.

1. Introduction

Images are captured using various photography tools that may not necessarily be in high quality. The color shifting problem causes the captured image to appear in low contrast and low color dynamic range, resulting in an image with important information lost. Therefore, image enhancement plays a vital role in various applications such as satellite imaging [1], medicine [2], and geography image acquisition [3]. It is the process of enhancing the visual information within the image. The existing image enhancement methods can be classified in three main categories [4]: histogram equalization techniques, Retinex-based algorithms [5,6], and unsharp masking techniques [7,8].

Contrast enhancement may be considered as a front-end solution in image enhancement to elicit important information from a low quality image taken in unsuitable conditions. Among various methods of contrast improvement, histogram equalization and histogram matching are the most common ones due to their simplicity and high efficiency [9,10]. Since image histogram is a useful description to display the information in an image, different histogram-based methods have been introduced to enhance image contrast. Celik proposed a two-dimensional histogram equalization method, which employed the contextual information around each pixel to improve the contrast of an input image [11]. In another study, contrast of an image was enhanced using spatial information of pixels [12]. This technique used spatial distribution of pixel gray levels, i.e., the distribution of spatial locations of gray levels in an image instead of gray-level distribution, to compute the spatial entropy of pixels. Kwak and Park introduced a contrast enhancement

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technique using multi-local histogram transformations for supervisory systems [13]. Recently, Wang and Chen proposed a novel histogram modification scheme, which improved image contrast [14]. The modified histogram was generated by Gamma correction and the mapping function was obtained by applying histogram equalization to the modified histogram. Finally, the image was enhanced uniformly while retaining the mean illumination. Although acceptable images can be obtained by these enhancement methods, their details cannot be improved well [15]. Therefore, other methods have been developed that enhance image contrast using other techniques such as bionic algorithms, e.g., bee colony algorithm [16] and genetic algorithm [17], or wavelet transform and entropy [18]. This study scales the high-frequency coefficients of an image in wavelet domain through magnified entropy, which can enhance the contrast.

Different techniques have also been introduced for improving color of images based upon the models of subjective human color vision. An iterative histogram matching algorithm was presented for color image enhancement based on statistical moments [19]. A texture-based color image enhancement methodology was proposed by Raji et al. [20] that focused on an automated way for target image generation. An adaptive enhancement algorithm based on HSV color space was proposed for enhancement of low-illumination color images [21]. A method was proposed for low-contrast color images enhancement using histogram and fuzzy logic [22]. The method operated based on two important parameters, namely illumination and contrast level, in HSV color space. A type of contrast resolution compensation algorithm was presented that operated based on human visual perception model [23]. In this approach, the image was transferred from RGB to HSV color space; then, components of V and S were processed to enhance image brightness and recover the image color information. Recently, Fu et al. [24] proposed a fusion-based method to enhance the weak-illumination images. After estimating the illumination by a morphological algorithm, a strategy based on weighting and fusion was used to improve the illumination. Sun et al. presented a novel image enhancement approach based on illumination-reflection model [25]. This study applied nonlinear functions for extracting the reflection component, which preserved the important features of the edges of image and improved it. An image enhancement method was proposed by Guo et al. that enhanced the visibility of image by changing the R, G, and B channels and building a new illumination map [26]. A trainable convolutional neural network was presented, which was able to obtain the illumination map from the input image and then, improve the image based on Retinex model [27].

As mentioned, although there are various image enhancement methods, it sounds necessary to develop more efficient methods than the existing ones, since the majority of existing the methods have two main problems; first, some of them enhance images with results that do not seem natural [28] and second, some techniques can improve only the outdoor images [29].

A two-stage technique is proposed in this paper to enhance both contrast and color of an image. In the first stage, after converting an RGB image to the HSV color space, its contrast is enhanced using automatic histogram matching. The color shifting effect would be more obvious in the contrast-enhanced image than in the original one. Hence, another method is applied to improve image color. The histograms of the V and S components of the image improved in the first stage are stretched.

The rest of the paper is organized as follows: Section 2 introduces the reference images database. The used similarity measure is presented in Section 3. Section 4 describes the proposed method and its algorithm. The results of applying the proposed method to several images and the conclusion are respectively provided in Sections 5 and 6.

2. Materials and methods

2.1. Reference images database

For automatic selection of the target image in histogram matching, good-contrast images from various scenes are required to enable the system to choose the most proper image. There was no suitable general database which we could use in our work. Hence, we made a database of 85 images. The database included images of forest landscapes, waterfalls, and rivers in different seasons as well as human faces and people with proper contrast. Some of the images (74 images) were collected from the internet by querying several image search engines. The database was diverse and constructed with different objects in various appearances, positions, viewpoints, and poses as well as background clutter and occlusion. The rest were images taken from NASA [30]. Some of the images in the database are shown in Figure 1. Our experiments will show that our collected database is suitable to enhance images via histogram matching.

2.2. Similarity measure

In order to measure the similarity between two histograms, a similarity measure can be used. There are many similarity measures, each of which is appropriate for a certain application [31,32]. In this study, Jensen similarity measure is used to measure the similarity between histograms of the original and target images [33,34]. This measure is a useful tool for assessing the similarity of time series with the same

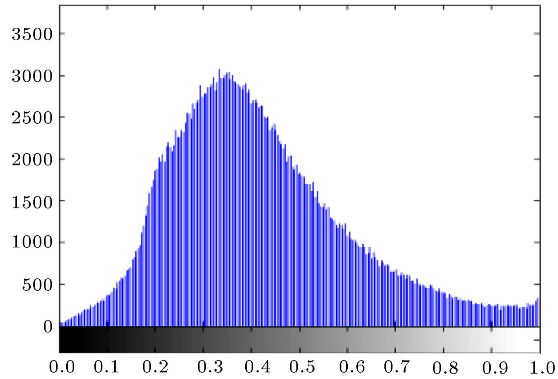
Figure 1. Sample images from our database.

length but various amplitudes, which is the case in measuring the similarity between histograms.

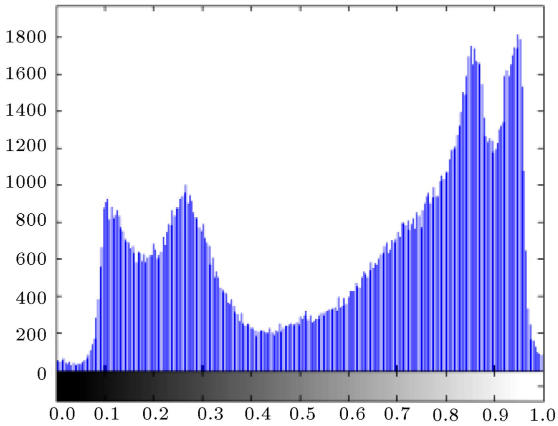
For two vectors $\mathbf{P} = \{\mathbf{p}_1, \mathbf{p}_2, \cdots, \mathbf{p}_k\}$ and $Q = \{\mathbf{q}_1, \mathbf{q}_2, \cdots, \mathbf{q}_k\}$ associated with the histograms of two images, the Jensen function is defined as follows:

$$\mathbf{J} = \frac{1}{2}\sum_{i=1}^{k}\Bigg\{\mathbf{p}_i'\log_2\mathbf{p}_i' + \mathbf{q}_i'\log_2\mathbf{q}_i' - (\mathbf{p}_i' + \mathbf{q}_i')\log_2\left(\frac{p_i' + q_i'}{2}\right)\Bigg\}, \tag{1}$$

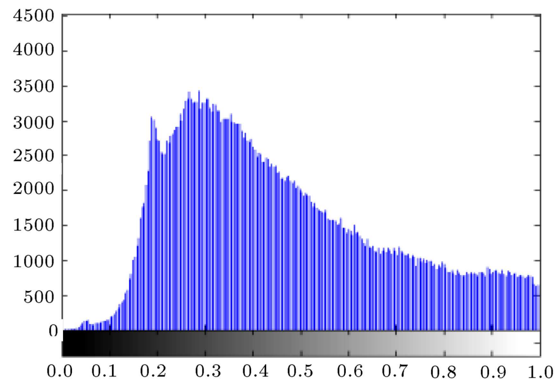
where:



(a)



(b)



(c)

Figure 2. (a) Histogram of the original image. (b) Histogram with less similarity ($J = 0.24$) to histogram (a). (c) Histogram with more similarity ($J = 0.019$) to histogram (a).

$$\mathbf{p}_i' = \mathbf{p}_i \Bigg/ \sum_{i=1}^{k}\mathbf{p}_i, \qquad \mathbf{q}_i' = \mathbf{q}_i \Bigg/ \sum_{i=1}^{k}\mathbf{q}_i.$$

The output of the Jensen function is between 0 and 1. If the two sequences P and Q are identical or very similar, the output of the Jensen function will be equal to 0.

Figure 2 shows three histograms associated with three different images. Similarity of the three histograms has been measured using the Jensen function. As seen, the calculated similarity value is a smaller number for the histograms which are more similar to each other.

2.3. The proposed method

Images suffering from low contrast are often accompanied by color shifting effect. Therefore, for improving these images, it is required to enhance both color and contrast. We propose to enhance the low-dynamic-range images in a two-stage approach.

In the first stage, for improving contrast, we use a histogram matching technique in which the reference image is automatically chosen from the database. In this approach, the images are considered in HSV color space. HSV contains three components: H (hue) refers to color wavelengths, S (saturation) indicates the ratio of the dominant wavelength to other wavelengths in the color, and V (value) determines lightness or darkness of a color. In enhancing the contrast of an image, its lightness (i.e., component V) should be taken into account. Hence, by comparing the V components of the input image and the images in the database using Jensen, the image with more similar brightness to the original image is selected as the target image for histogram matching. Finally, the image contrast is enhanced by applying the histogram matching technique to the V component of the image.

As the brightness of the image after applying the first stage is improved, the existence of color shifting effect would be more obvious in the contrast-enhanced image. Hence, it may also be required to improve the color information of the image in the second stage of image enhancement.

In the second stage, we use the histogram stretching technique of min-max based sub-image-clipped introduced in [35]. We obtain the histograms of components S and V of the image processed in the first stge. Then, we find the maximum and minimum points in each histogram. The minimum intensity point $i_{\min}$ refers to the lowest intensity value in the image histogram, whereas the maximum intensity value $i_{\max}$ refers to the highest intensity value. The mid-point of the intensity level i_{mid} of a histogram is calculated using Eq. (2). Figure 3 illustrates an example of these points in a histogram.

$$i_{mid} = \frac{i_{\max} - i_{\min}}{2} + i_{\min}. \tag{2}$$

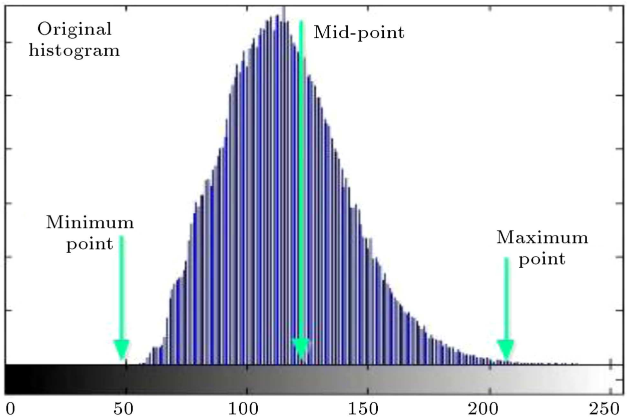


Figure 3. The maximum, minimum, and middle points of an image histogram.

Since brightness of image is shown in component V, we process the V component to overcome under- or over-enhanced areas possibly brought forth in the first step. The S component is also processed for improving the color information of the image. Hence, each histogram is divided into two regions, namely lower and upper. Each region is then stretched as follows:

a) The lower region, from $i_{\min}$ to the mid-point i_{mid}, is stretched towards the higher-intensity level with the minimum output value of 1% from the minimum intensity value of the dynamic range;

b) The upper region, from i_{mid} to the maximum intensity value $i_{\max}$, is stretched towards the lower-intensity level with the maximum output value of 1% from the maximum intensity value of the dynamic range.

The above limits are set in order to prevent the S and V components from exceeding their minimum and maximum values, which can lead to under- or over-brightness of the image. The stretching (1%) is done to decrease the effect of dominant color channels and it is empirically chosen. The resultant images with a bigger limiting value are very over-enhanced. Figure 4 illustrates this stretching process for a given histogram.

The stretching process produces two stretched histograms associated with the S and V components. The lower- and upper-stretched histograms of S are integrated by means of the average value (Eq. (3)), as shown in Box I.

The same integration process is applied to component V, where the lower- and upper-stretched his-

$$\text{Average} = \frac{(\text{lower-stretched histogram}) + (\text{upper-stretched histogram})}{2}. \tag{3}$$

Box I

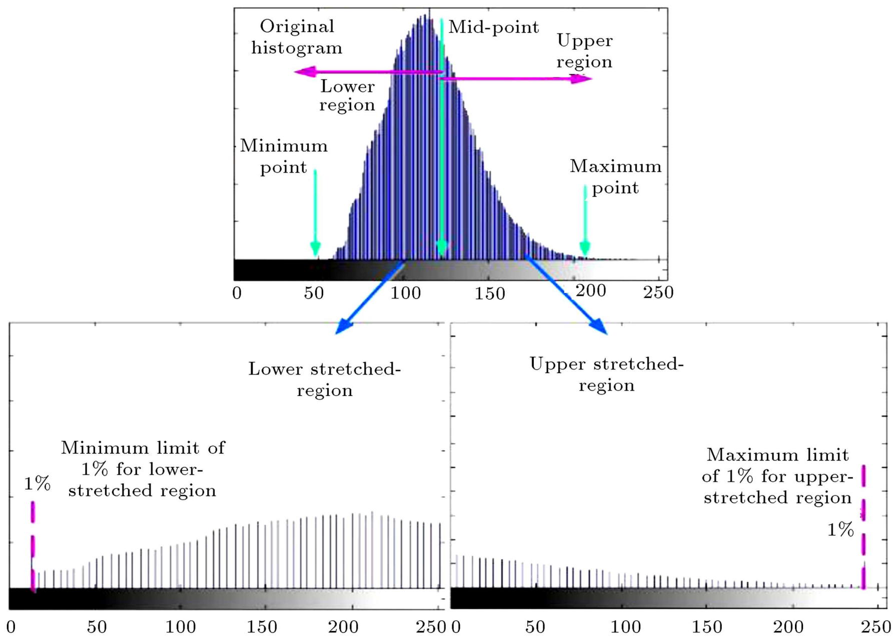


Figure 4. Division and stretching of the histogram to produce lower- and upper-stretched regions.

tograms are integrated. Then, H, S, and V components are composed to produce an image in HSV color model. Finally, the enhanced image is converted to RGB by inverse transform. Figure 5 shows the resultant images after performing each step on the image. The effect of stretching 1% on the histograms is clear in this figure.

As mentioned, in the first stage, image contrast is enhanced based on the chosen target image and this process may interfere with the color purity in some regions. Therefore, in the second stage, we simultaneously change the histograms of both components S and V of the image produced in the first stage in order to solve this potential problem. Indeed, the process in the second stage resolves the problem of under- and over-enhanced regions.

The execution time of the proposed method is reasonable. The average execution time per different images with the average size of $838 * 627$ is 10 seconds in a system with 4GB RAM, Intel core i2, 2.10 GHz CPU. Also, if we save the histograms of the database images, the average execution time decreases by nearly 2.06 seconds.

3. Results

We considered several images in RGB color space to examine the capability of the proposed method in image enhancing. Figure 6 shows the results of applying the proposed method to a number of images. As seen, all of the processed images have considerably better contrast with more pleasant color.

To compare the results of the proposed method with the results of other existing methods, we choose the methods introduced in [18,21,22], and [25-27], which are used to enhance color images. In addition to these techniques, the proposed method is compared with CLAHE (Contrast-Limited Adaptive Histogram Equalization) [36] method that has widely been used by other researchers for comparison.

We evaluate the proposed method based on qualitative observation and quantitative measurements. Through the quantitative analysis, the proposed method is evaluated in terms of entropy, MSE, PSNR, SSIM, and Sobel edge detection. Entropy can be considered as corresponding states of gray level which individual pixels can acquire [37]. Entropy represents the abundance of image information. MSE and PSNR are two error metrics used in order to compare the quality of resultant images. The SSIM considers image degradation in structural information. To evaluate the capability and performance of their proposed methods, several researchers used edge detection on the basis of the number of edges found in an image [38,39]. This is carried out by counting the number of edges detected using Sobel edge detector. A high number of edges is desired as it shows that the image has high feature content. However, the number of counted edges should be balanced with the value of MSE or PSNR and, therefore, the high number of Sobel edges should be balanced with the low value of MSE (or high value of PSNR).

To indicate the contribution of the first stage, we only show the results of performing the second stage, both qualitatively and quantitatively, in Figure 7. Both of the results show that the first step has a positive effect. Besides good contrast and color, PSNR,

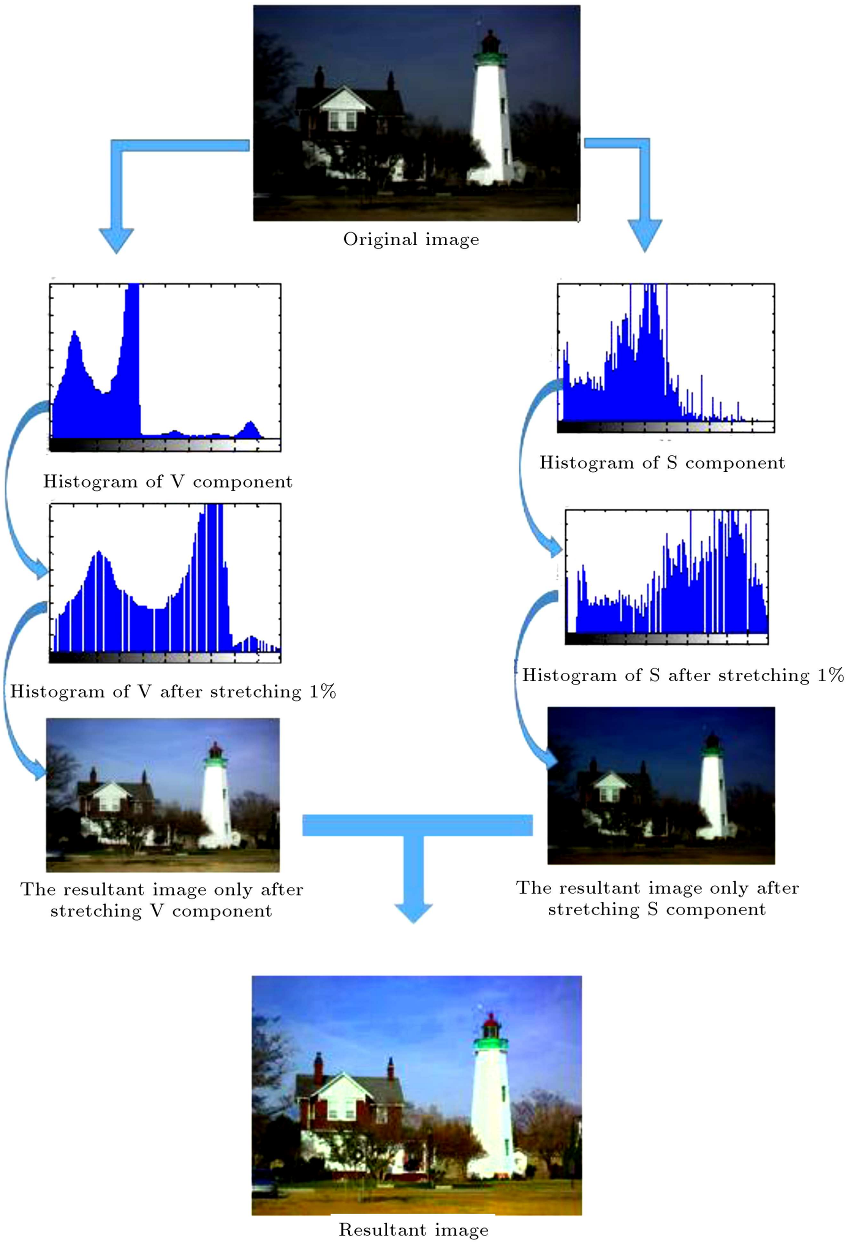


Figure 5. Illustration of going through the second stage of the proposed method for an image.

SSIM, and entropy show that the resultant images, after applying the two stages, well keep structure and information of the original image.

4. Discussion

Figures 8 and 9 show three images which are enhanced by the introduced methods. These figures show that the details are seen in high resolution. Also, details of the enhanced images by the proposed method are more obvious. Quantitative results for the sample images in Figures 8 and 9 are provided in Tables 1 and 2. Table 3 shows the quantitative average results obtained by comparing the proposed method with other studies by applying them to 200 images from MIT-Adobe FiveK Dataset [40]. High values of entropy, PSNR, SSIM, and Sobel edge detection are desired as they show that the images contain more information features. On the other hand, the low value of MSE is desired as it shows that the resultant images have less noise. In Tables 1-3, the bold-typeface values indicate the best results obtained in the comparison.

As the second image in Figure 8 shows, the outcome of the method in [21] is very bright and looks unnatural, in which the sun is shining at the time the photo is taken. The entropy of the results obtained using the method in [21] shows that it is not as successful in providing information as other

Figure 6. Result of applying the proposed method to images; the top row contains the original images and the second row shows enhanced images by the proposed method.

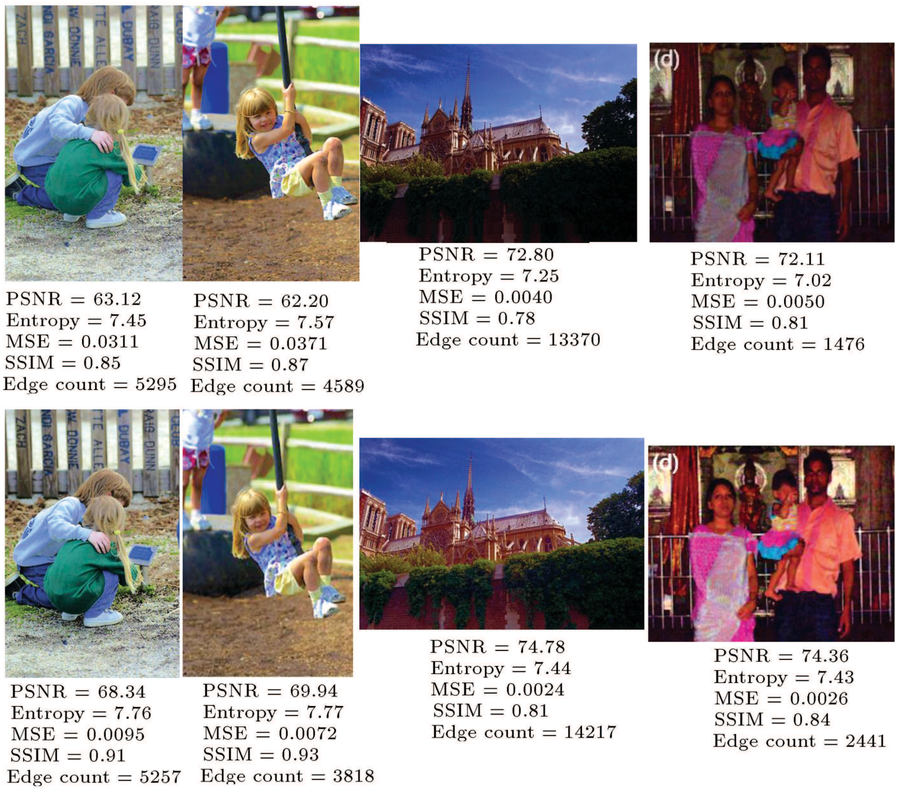


Figure 7. (a) Resultant images only by the second stage of the proposed method. (b) Results of the proposed method (by both the first and second stages).

methods. It has the lowest value after CLAHE. The images produced by CLAHE have a good contrast as the resultant image is clearly seen. However, based on observation, the quality of image color is reduced.

For the CLAHE method, the over-enhanced problem can be observed in the resultant image in Figure 8(a). The tree areas on the left of the house become darker and the tower is over-saturated as the pixels are too bright. This effect causes the image to lose its details. The quantitative result agrees with the

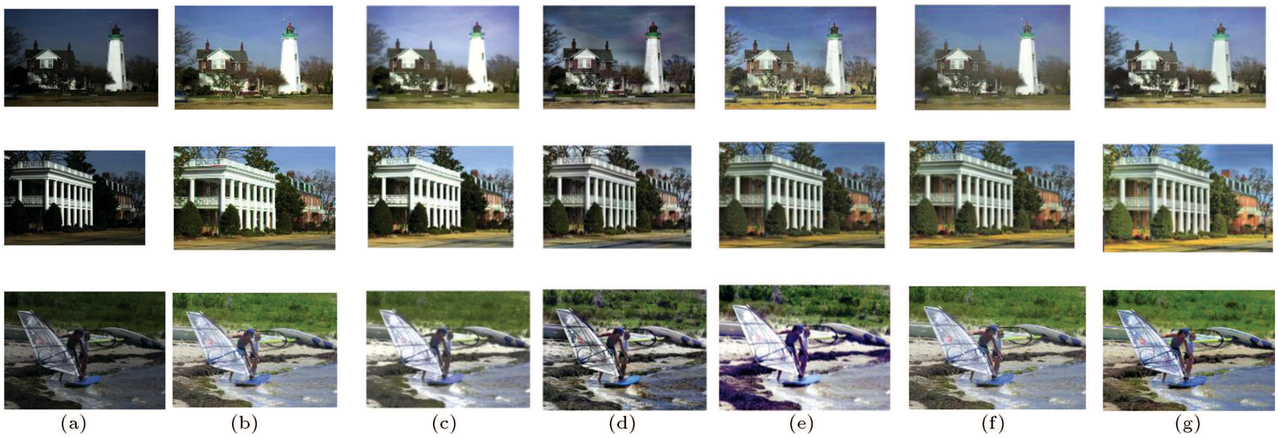


Figure 8. Results of applying the methods to images: (a) The proposed method and (b)-(g) the methods introduced in [21,22,36] and the CLAHE method in [18,25].

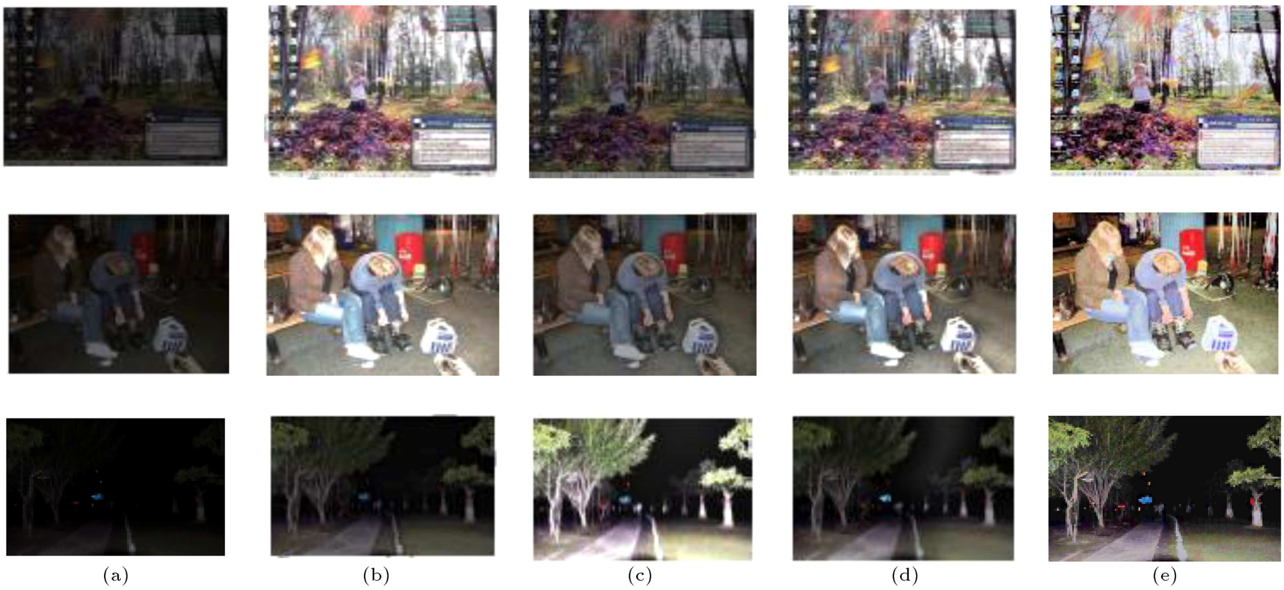


Figure 9. Results of applying the methods to images: (a) The proposed method and (b)-(e) the methods introduced in [24,26,27] and the CLAHE method in [18,25].

observation as the entropy value of the resultant image produced by CLAHE is the lowest. The highest Sobel count by CLAHE may result from the noise produced in the process as the resultant image has the highest MSE value. It is observed that the proposed method enhances the image better, as the contrast of the resultant image is balanced and the areas are not too dark or too bright. The proposed method significantly increases image contrast at the fore- and background, since both areas are significantly enhanced. This observation is supported by the quantitative result as the resultant image produced by the proposed method has the highest entropy value. In addition to the highest entropy value, the proposed method almost has the lowest MSE and the highest PSNR and SSIM. As seen in Figure 9, the resultant images of the proposed method seem natural and their details are obvious. For instance, in the third image, the signs and lights along the road are shown clearly. Moreover, it is clear in Figure 9 that the contrast of the first and second resultant images is enhanced by applying the method in [26]; however, the brightness and quality of images are not proper. In fact, they do not seem natural. By looking at the average results in Table 3, the superiority of the proposed method is noticeable as it has the highest values in measurements among all techniques. As said before, it has a reasonable processing time. Table 4 shows a comparison of the execution times of the proposed method and other state-of-the-art techniques. All methods are applied in a computer with Intel core i2, 2.10 GHz CPU and 4 GB RAM and the processing times for the images with the size of 838*627 are measured. It is noticeable that the proposed method is the least time-consuming

Table 1. Quantitative results for the sample images in Figure 8 (high values of PSNR, SSIM, and entropy show more successful methods).

	Method	Entropy	MSE	PSNR	SSIM	Sobel count
Figure 8(a)	Original image	7.1455	—	—	—	3314
	[18]	7.7265	6852.4	13.845	0.93	4145
	[21]	4.9553	9189.9	8.4982	0.92	7233
	[22]	7.7529	7325.3	14.459	0.87	2071
	[25]	6.8885	3017.2	16.5804	0.84	5033
	CLAHE [36]	3.9345	9597.1	8.3096	0.72	6673
	Proposed method	**7.8516**	**2330.2**	**19.487**	**0.98**	**3818**
Figure 8(b)	Original image	6.9816	—	—	—	2567
	[18]	7.5821	3295.6	13.105	0.91	2754
	[21]	4.9185	8862.5	8.6553	0.89	6126
	[22]	7.7342	3476.0	12.725	0.82	1864
	[25]	6.8817	4602.2	12.7849	0.88	4624
	CLAHE [36]	3.9417	9376.7	8.4106	0.68	6135
	Proposed method	**7.8438**	**2788.3**	**13.706**	**0.94**	**3858**
Figure 8(c)	Original image	6.9312	—	—	—	3796
	[18]	6.9541	2045.1	16.485	0.92	2415
	[21]	4.9185	8174.0	9.0075	0.89	6126
	[22]	7.7342	2175.5	17.083	0.87	1864
	[25]	6.8817	7901.9	16.1554	0.84	6624
	CLAHE [36]	3.9417	8680.7	8.7466	0.72	6135
	Proposed method	**7.8438**	**1276.3**	**17.758**	**0.96**	**3858**

Table 2. Quantitative results for the sample images in Figure 9 (high values of PSNR, SSIM, and entropy show more successful methods).

	Method	Entropy	MSE	PSNR	SSIM	Sobel count
Figure 9(a)	Original image	7.2965	—	—	—	3241
	[24]	7.5295	3484.6	15.8145	0.89	4885
	[26]	7.3573	3125.9	16.4582	0.93	2233
	[27]	7.7249	2825.7	16.9939	0.91	2151
	Proposed method	**7.8974**	**1904.0**	**18.487**	**0.97**	**3584**
Figure 9(b)	Original image	7.4152	—	—	—	3574
	[24]	7.4225	3425.7	11.454	0.85	2755
	[26]	7.3685	3162.4	11.783	0.87	3961
	[27]	7.4745	3067.0	12.051	0.88	3445
	Proposed method	**7.7148**	**2888.4**	**12.460**	**0.92**	**3682**
Figure 9(c)	Original image	6.8974	—	—	—	2748
	[24]	6.4511	1842.7	16.845	0.81	1847
	[26]	6.9815	1674.9	17.425	0.88	3050
	[27]	6.8432	1552.8	17.934	0.92	2185
	Proposed method	**7.1348**	**1347.4**	**18.382**	**0.98**	**2876**

Table 3. Average quantitative results for 200 images in MIT-Adobe FiveK Dataset [40] in comparison with other studies.

Method	Entropy	MSE	PSNR	SSIM	Sobel count
Original image	7.2533	—	—	—	3238
[18]	7.7304	4525.7	14.7466	0.85	1936
[21]	7.0645	3515.4	16.1452	0.89	4201
[22]	4.9407	8741.13	8.7303	0.87	6495
[25]	6.8839	4507.1	17.4504	0.90	4565
CLAHE [36]	3.7693	9216.4	8.8448	0.68	6214
Proposed method	**7.8564**	**2031.6**	**17.9863**	**0.94**	**3849**

Table 4. Processing times (s) of various image enhancement methods.

[14]	[16]	[18]	[24]	[25]	The proposed method
3.875	885.73	4.7	3.17	4.36	2.06

method among all techniques by using uncomplicated algorithms, rather than evolutionary algorithms or neural networks, for enhancing images.

5. Conclusion

We proposed a method which could enhance both contrast and color of images suffering from low contrast or low color dynamic range. In a two-stage method, after converting the RGB images to HSV, an automatic method for selecting target image in histogram matching was suggested and the contrast of input image was enhanced. The target image was automatically selected from the database containing 85 reference images using a similarity measure. In the second stage, histogram stretching was employed to correct the color of the contrast-enhanced image. We showed the success of this method in contrast and color enhancement by comparing the results of the proposed method and eight other methods. It could also enhance improper contrast and color images.

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