Hue-Preserving Color Image Enhancement Without Gamut Problem

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***Abstract*—The first step in many techniques for processing intensity and saturation in color images keeping hue unaltered is the transformation of the image data from RGB space to other color spaces such as LHS, HSI, YIQ, HSV, etc. Transforming from one space to another and processing in these spaces usually generate gamut problem, i.e., the values of the variables may not be in their respective intervals. Enhancement techniques for color images are studied here theoretically in a generalized setup. A principle is suggested to make the transformations' gamut problem free in this regard. Using the same principle a class of hue preserving contrast enhancement transformations are proposed, which generalize the existing grey scale contrast intensification techniques to color images. These transformations are also seen to bypass the above mentioned color coordinate transformations for image enhancement. The developed principle is used to generalize the histogram equalization scheme for grey scale images to color images.**

***Index Terms*—Contrast stretching, enhancement, gamut problem, histogram specification, hue, hue preserving transformation, intensity, saturation, scaling, shifting.**

I. INTRODUCTION

IMAGE enhancement is used to improve the quality of an image for visual perception of human beings. It is also used for low level vision applications. It is a task in which the set of pixel values of one image is transformed to a new set of pixel values so that the new image formed is visually pleasing and is also more suitable for analysis. The main techniques for image enhancement such as contrast stretching, slicing, histogram equalization, for grey scale images are discussed in many books. The generalization of these techniques to color images is not straight forward. Unlike grey scale images, there are some factors in color images like hue which need to be properly taken care of for enhancement. These are going to be discussed here.

Hue, saturation and intensity are the attributes of color [1]. Hue is that attribute of a color which decides what kind of color it is, i.e., a red or an orange. In the spectrum each color is at the maximum purity (or strength or richness) that the eye can appreciate, and the spectrum of colors is described as fully saturated. If a saturated color is diluted by being mixed with other colors or with white light, its richness or saturation is decreased [2]. For the purpose of enhancing a color image, it is to be seen that hue should not change for any pixel. If hue is changed then the color gets changed, thereby distorting the image. One needs to improve the visual quality of an image without distorting it for image enhancement. Several algorithms are available for contrast enhancement in grey scale images, which change the grey values of pixels depending on the criteria for enhancement. On the other hand, literature on the enhancement of color images is not as rich as grey scale image enhancement. In this regard, a short survey of the literature on color image enhancement is described below.

Strickland *et al.* [3] proposed an enhancement scheme based on the fact that objects can exhibit variation in color saturation with little or no corresponding luminance variation. Thomas *et al.* [4] proposed an improvement over this method by considering the correlation between the luminance and saturation components of the image locally. Toet [5] extended Strickland's method [3] to incorporate all spherical frequency components by representing the original luminance and saturation components of a color image at multiple spatial scales.

Four different techniques of enhancement, mainly applicable in satellite images, based on "decorrelation stretching" [6] and rationing [7] of data from different channels are proposed by Gillespie *et al.* Gupta *et al.* proposed a hue preserving contrast stretching scheme for a class of color images in [8]. A genetic algorithm (GA) approach in which the enhancement problem is formulated as an optimization problem is suggested by Shyu *et al.* [9]. Lucchese *et al.*'s [10] method for color contrast enhancement works in xy-chromaticity diagram, which consists of two steps : (1) transformation of each color pixel into its maximally saturated version with respect to a certain color gamut and (2) desaturation of this new color toward a new white point.

Pitas *et al.* proposed a method to jointly equalize the intensity and saturation components in [11]. In [12], Buzulois *et al.* proposed an adaptive neighborhood histogram equalization algorithm. A 3-D histogram specification algorithm in RGB cube with the output histogram being uniform is proposed by Trahanias *et al.* [13]. Mlsna *et al.* [14] proposed a multivariate enhancement technique "histogram explosion", where the equalization is performed on a 3-D histogram. This principle is later extended to CIE LUV space [15]. The same authors later proposed a recursive algorithm for 3-D histogram enhancement scheme for color images [16].

Bockstein *et al.* [17] proposed a color equalization method based on both saturation and brightness of the image. Weeks *et al.* [18] proposed a hue preserving color image enhancement technique which modifies the saturation and intensity components in color difference (C-Y) color space. Their algorithm partitions the whole (C-Y) color space into $n \times k$ number of subspaces, where n and k are the number of partitions in luminance and saturation components respectively. Saturation is

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equalized once for each of these n $\times$ k subspaces within the maximum realizable saturation of the subspace. Later the luminance component is equalized considering the whole image at a time. To take care of the R, G, and B values exceeding the bounds, Weeks *et al.* suggested to normalize each component using $(255)/(\max(\mathrm{R}, \mathrm{G}, \mathrm{B}))$.

Yang *et al.* [19] proposed two hue preserving techniques, namely, scaling and shifting, for the processing of luminance and saturation components. To implement these techniques one does not need to do the color coordinate transformation. Later, the same authors have developed clipping techniques [20] in LHS and YIQ spaces for enhancement to take care of the values falling outside the range of RGB space. Clipping is performed after the enhancement. A high resolution histogram equalization of color images is proposed in [21]. The effect of quantization error in the quantization of the luminance in histogram equalization is also studied.

Though the algorithms reported above are interesting and effective for enhancement, most of them do not effectively take care of the gamut problem – the case where the pixel values go out of bounds after processing. Due to the nonlinear nature of the uniform color spaces, conversion from these spaces with modified intensity and saturation values to RGB space generates gamut problem. In general this problem is tackled either by clipping the out of boundary values to the bounds or by normalization [17], [18], [9]. Clipping the values to the bounds creates undesired shift of hue. Strickland has discussed the problem of clipping in [3]. Normalization reduces [9] some of the achieved intensity in the process of enhancement which is against its objective. Weeks *et al.* [18] also mentioned that luminance may be modified due to rescaling.

In this article we have suggested a novel and effective way of tackling the gamut problem during the processing itself. It is not necessary to bring back the R, G, and B values to its bounds after the processing is over in this method. Proposed algorithm does not reduce the achieved intensity by the enhancement process. The enhancement procedure suggested here is hue preserving. It generalizes the existing grey scale image enhancement techniques to color images. The processing has been done in RGB space and the saturation and hue values of pixels are not needed for the processing.

The results obtained from the proposed methods have been compared with the results obtained from the clipping techniques proposed by Yang *et al.* [20] and the histogram equalization algorithm proposed by Weeks *et al.* [18].

This article is organized in the following way. In Section II, a general hue preserving transformation is proposed for image enhancement. In Section III, a linear contrast enhancement transformation is described. In Section IV, a general principle for gamut problem free, hue preserving, nonlinear transformation is developed. Section V provides the comparison of the results of the proposed method and existing methods. Section VI contains conclusion and discussion.

II. HUE PRESERVING TRANSFORMATIONS

Hue preservation is necessary for color image enhancement. Distortion may occur if hue is not preserved. The hue of a pixel in the scene before the transformation and hue of the same pixel after the transformation are to be same for a hue preserving transformation. In this section, the aim is the development of a general hue preserving transformation for contrast enhancement.

In general, color images are stored and viewed using RGB color space. To process an image for enhancement in any of the above mentioned spaces (i.e., LHS, HSI, YIQ, etc.), the image needs to be transformed to that space. The transformations involved in changing the color image from RGB space to other mentioned spaces are, generally, computationally costly [19] and again the inverse coordinate transformation has to be implemented for displaying the images. Two operations, *scaling* and *shifting*, are introduced in [19], [20] for luminance and saturation processing. Scaling and shifting are hue preserving operations [19], [20]. Using these two operations hue preserving contrast enhancement transformations are developed in this section.

To explain scaling and shifting in a mathematical fashion let us denote the normalized grey values for R, G, and B components of a pixel of an image I by a vector $\tilde{x}$, where, $\tilde{x} = (x_1, x_2, x_3)$, x_1, x_2, x_3 correspond to the normalized *red, green* and *blue* pixel values respectively. That is, $0 \leq x_k \leq 1$, $k = 1$, 2, 3.

Scaling: Scaling the vector $\tilde{x}$ to $\tilde{x}'$ by a factor $\alpha > 0$ is defined as $\tilde{x}' = (x_1 \cdot \alpha,\ x_2 \cdot \alpha,\ x_3 \cdot \alpha)$.

Shifting: Shifting a vector $\tilde{x}$ to $\tilde{x}'$ by a factor β is defined as $\tilde{x}' = (x_1 + \beta,\ x_2 + \beta,\ x_3 + \beta)$.

A transformation which is a combination of scaling and shifting can be written as

$$\tilde{x}' = (\alpha x_1 + \beta,\ \alpha x_2 + \beta,\ \alpha x_3 + \beta). \tag{1}$$

Note that in (1), x'_k is linear in x_k $\forall$k, and α and β are not dependent upon $\tilde{x}$.

It can be shown that the transformation, as given in (1), is hue preserving. The expression of hue considered here is the hue as defined in HSI space. It is known in the literature [19], [20] that linear transformations are hue preserving. However for the purpose of clarity and continuity of the investigation, the above material is provided here.

Note that in (1), α and β are not dependent upon $\tilde{x}$. A general transformation in which α and β vary with each $\tilde{x}$ but same $\forall\ k = 1$, 2, 3, is defined as

$$x'_k = \alpha(\tilde{x}) x_k + \beta(\tilde{x}),\ k = 1, 2, 3. \tag{2}$$

Note that, in (2), α and β are functions of $\tilde{x}$. It can be shown from elementary mathematics that the color vector $\tilde{x}'$ as defined in (2) possesses the same hue as the color vector $\tilde{x}$ for any two functions α and β. In other words, one can obtain several (in fact uncountable) nonlinear hue preserving transformations by varying the functions α and β, as defined in (2). In the next section, we shall study the two functions α and β involved in (2) for obtaining the mathematical expression of linear transformation for enhancement.

III. Linear Transformations

Linear transformations are common for grey scale image enhancement. If we take $\alpha(\tilde{x})$ and $\beta(\tilde{x})$ as constant functions in (2), it will reduce to a linear transformation as follows:

$$\begin{aligned} x'_k &= \alpha x_k + \beta \text{ or} \\ x'_k &= \alpha_1 \cdot (x_k + \beta_1), \ \forall \, \tilde{x} \in I, \ k = 1, 2, 3 \end{aligned} \tag{3}$$

where x_k is the grey value of the kth component of the pixel, x'_k is the modified grey value of the kth component of the pixel, $\alpha_1 = \alpha$, and $\beta_1 = \beta/\alpha$.

Note that x_k's are normalized pixel values. Hence $x_k \in [0,1] \, \forall \, k = 1, 2, 3$. We would like to make $x'_k \in [0,1] \, \forall \, k$. Then α_1 must be non negative since $x'_k \geq 0 \, \forall \, k$. To achieve maximum contrast the pixel values, after the transformation, should spread over the whole range i.e., from 0 to 1. It can be clearly seen that if $\beta_1 = -\min_{k,\tilde{x}\in I}\{x_k\}$ and $\alpha_1 = 1/\max_{k,\tilde{x}\in I}\{x_k\}$, (3) provides a hue preserving linear transformation with maximum possible contrast. This method basically provides a linear stretching of pixel values by the same amount for each component.

IV. Non-Linear Transformations

In this section we try to generalize the usual grey scale contrast enhancement techniques to color images in such a way that they are hue preserving. The objective is to keep the transformed values within the range of the RGB space, i.e., the transformations are free from gamut problem. Some general and widely used contrast enhancement techniques for grey scale images are S-type enhancement, piecewise linear stretching, clipping etc. The methodologies of these techniques can be found in the literature. Only S-type transformation is listed below for grey scale images.

Let *'f'* denote the enhancement function. Let x represents the pixel value. Thus $x, f(x) \in [\delta_1, \delta_2]$, where $\delta_1 = 0$, $\delta_2 = 1$

$$f_{m,n}(x) = \begin{cases} \delta_1 + (m - \delta_1)\left(\frac{x-\delta_1}{m-\delta_1}\right)^n, & \delta_1 \leq x \leq m \\ \delta_2 - (\delta_2 - m)\left(\frac{\delta_2 - x}{\delta_2 - m}\right)^n, & m \leq x \leq \delta_2 \end{cases} \tag{4}$$

where m and n are two constants, $n \in (0, \infty)$, $m \in [\delta_1, \delta_2]$. This transformation is written in most general form. If $\delta_1 = 0$, $\delta_2 = 1$, $n = 2$ and $m = 0.5$, it provides the standard S-type contrast enhancement.

The above listed transformation is one dimensional but a pixel in a color image has a color vector with three components R, G, and B. The procedure followed for generalizing grey scale contrast intensification to color images is discussed below.

A generalized transformation changing $\tilde{x}$ to $\tilde{x}'$ is given as

$$x'_k = \alpha(x_k)x_k + \beta(x_k) \, \forall \, \tilde{x} \in I, \ k = 1, 2, 3. \tag{5}$$

This transformation is a most generalized transformation, where α and β can be any two functions. Looking into the increasing complexity of the problem, the shifting function $\beta(x_k)$ is taken to be zero $\forall \, k = 1, 2, 3$ and $\tilde{x} \in I$. To simplify the mappings still further, the linear transformation as described in previous section, is applied initially. Non-linear transformation is applied on the changed color vectors. Applying initially the said linear transformation stretches the intervals of the color levels linearly so that the pixel values will be spread to the maximum possible extent for each of the intervals for R, G, and B. After taking $\beta(x_k)$ to be zero $\forall \, k$ and $\tilde{x} \in I$ in the (5), the transformation would become

$$x'_k = \alpha(x_k)x_k \ \forall \ \tilde{x} \in I, \ k = 1, 2, 3. \tag{6}$$

In the above equation, α is a function of x_k i.e., it modifies the three components of the color vector by three different scales. This leads to change in hue of the color vector, which is against our aim. A way of making this transformation hue preserving is to have the same scale for each of the three components of the vector. It is already shown that this type of scaling is hue preserving. In particular, α can be taken as a function of $\ell_{\tilde{x}}$, where $\ell_{\tilde{x}} = x_1 + x_2 + x_3$. Then the transformation will be of the form

$$x'_k = \alpha(\ell_{\tilde{x}})x_k \ \forall \ \tilde{x} \in I, \ k = 1, 2, 3. \tag{7}$$

Initially, we define $\alpha(\ell_{\tilde{x}}) = f(\ell_{\tilde{x}})/\ell_{\tilde{x}}$, where $f(\ell_{\tilde{x}})$ is a nonlinear transformation used in contrast enhancement for grey scale images. For example, S-type transformation is listed earlier in this section. In the present case we can take $\delta_1 = 0$ and $\delta_2 = 3$. i.e., $\ell_{\tilde{x}}, \ f(\ell_{\tilde{x}}) \in [0, 3]$. As $\alpha(\ell_{\tilde{x}})$ is a ratio of $f(\ell_{\tilde{x}})$ and $\ell_{\tilde{x}}$, when $f(\ell_{\tilde{x}}) > \ell_{\tilde{x}}$, value of $\alpha(\ell_{\tilde{x}})$ will be greater than 1. In such a case value of x'_k may exceed 1 and thus resulting in gamut problem. A possible solution to this is to transform the color vector to CMY space and process it there. This will be dealt with in two separate cases.

Case 1) $\alpha(\ell_{\tilde{x}}) \leq 1$.

$$x'_k = \alpha(\ell_{\tilde{x}}) \, x_k \ \ \forall \, k = 1, 2, 3.$$

Case 2) $\alpha(\ell_{\tilde{x}}) > 1$.

1) Transform the RGB color vector $\tilde{x}$ to CMY color vector $\tilde{y}$ by $\tilde{y} = (y_1, \ y_2, \ y_3)$, where $y_k = 1 - x_k$, $k = 1, 2, 3$.
2) Find $\ell_{\tilde{y}} = y_1 + y_2 + y_3 = 3 - \ell_{\tilde{x}}$.
3) Find $g(\ell_{\tilde{y}}) = 3 - f(\ell_{\tilde{x}})$, $\alpha(\ell_{\tilde{y}}) = g(\ell_{\tilde{y}})/\ell_{\tilde{y}}$, Note that $\alpha(\ell_{\tilde{y}}) < 1$.
4) $y'_k = \alpha(\ell_{\tilde{y}}) \, y_k \ \ \forall \, k = 1, 2, 3$
5) Back to RGB space by the transformation

$$\tilde{x}' = (1 - y'_1, \ 1 - y'_2, \ 1 - y'_3) \ \ \clubsuit.$$

A color image enhancement principle has been stated above. Some salient points regarding the above principle are stated below.

i) In the proposed principle, intensity of a pixel is getting modified with the help of the contrast enhancement function *'f'*. Different contrast enhancement functions provide different importance to pixels. But α need not always be a function of intensity. There can be several hue preserving α functions whose functional forms are not dependent upon the intensity, $x_1 + x_2 + x_3$ of the pixel. *ii*) Any grey scale image enhancement scheme can be generalized to color images with the above principle. *iii*) The above method also possesses another desirable property i.e., if the enhancement function *'f'* preserves the orderings of $\ell_{\tilde{x}}$ then above method also preserves the same orderings. (*iv*)

Fig. 1. Lenna image of size 256 × 256.

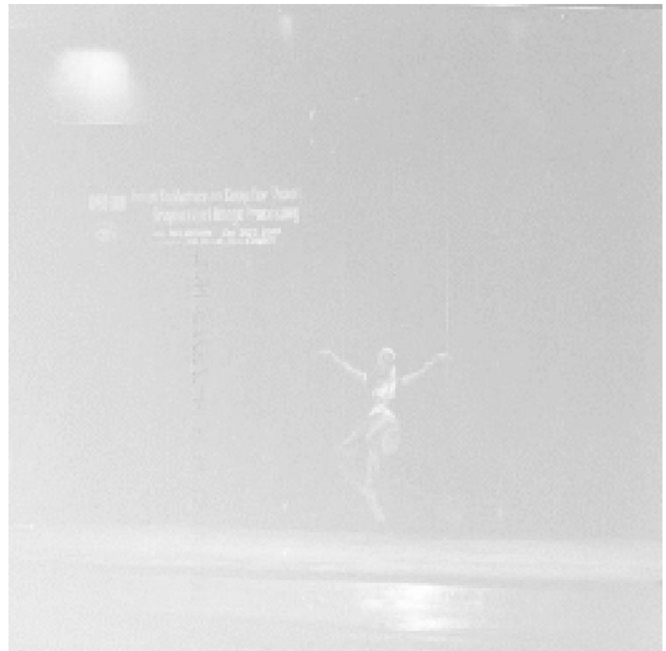


Fig. 2. Dancer image of size 256 × 256.

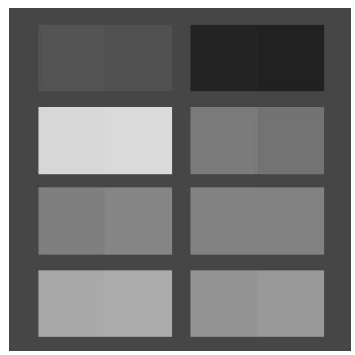


Fig. 3. Artificial image of size 128 × 128.

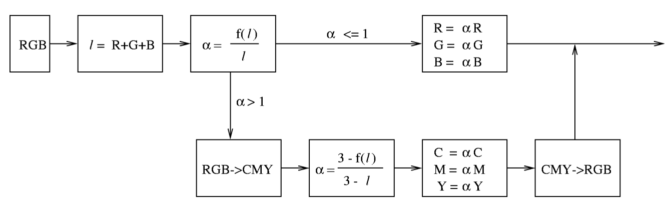


Fig. 4. Block diagram of the proposed enhancement scheme.

Note that, initially, linear transformation, as developed in the previous section, is applied on each of the pixels to extend the interval for each of R, G, and B to the maximum possible extent. We believe that nonlinear hue preserving transformation without gamut problem can be developed without initially applying the linear transformation, though, we have not attempted to find one such transformation here. The block diagram for the proposed scheme is shown in Fig. 4. (*v*) A good hue preserving transformation should not map a pixel having nonzero saturation to a pixel having saturation zero. Otherwise, hue of the pixel becomes undefined. Using the same principle developed in this section, such a case will not arise unless it is a digitization error or the enhancement function 'f' maps a $\ell_{\tilde{x}} \neq 0$ or 3 to either 0 or 3. (*vi*) It should be noted that, whenever any $\ell_{\tilde{x}} \neq 0$ or 3 is mapped to either 0 or 3, the corresponding pixel becomes a black or a white pixel respectively. Individual care should be taken at the time of choosing the constants involved in the transformations while implementing different enhancement functions to make the transformations completely hue preserving.

A. Histogram Equalization

Histogram equalization is a very powerful scheme for contrast enhancement in grey scale images. In grey scale histogram equalization, the method rearranges the grey values in such a way that the modified histogram resembles the histogram of uniform distribution. Intuitively, the same technique should work on a color image also, i.e., by equalizing the image in three dimensional space where the three dimensions are the three primary components of the color space. But this causes unequal shift in the three components resulting in change of hue of the pixel [9]. A solution is to equalize only the luminance/saturation or both the components in the color spaces such as LHS, HSI, or YIQ. This sometimes leads to gamut problem when the processed data is again transformed back to RGB space. Using the principle mentioned previously this problem can be avoided i.e., equalize the intensity $\ell_{\tilde{x}}$ in $[\delta_1, \delta_2]$ and let the equalization function be $f(\ell_{\tilde{x}})$ and then follow the steps of the algorithm as in the case of nonlinear enhancement. The same principle works for any histogram specification problem. To eliminate the cases of undefined hue, values of δ_1 and δ_2 are to be chosen properly.

V. Results and Comparisons

Two real life images namely, Lenna (Fig. 1), Dancer (Fig. 2), and one artificial image (Fig. 3) are considered for showing the results and comparison with other methods. Lenna image has good contrast. Dancer image is a noisy image because of

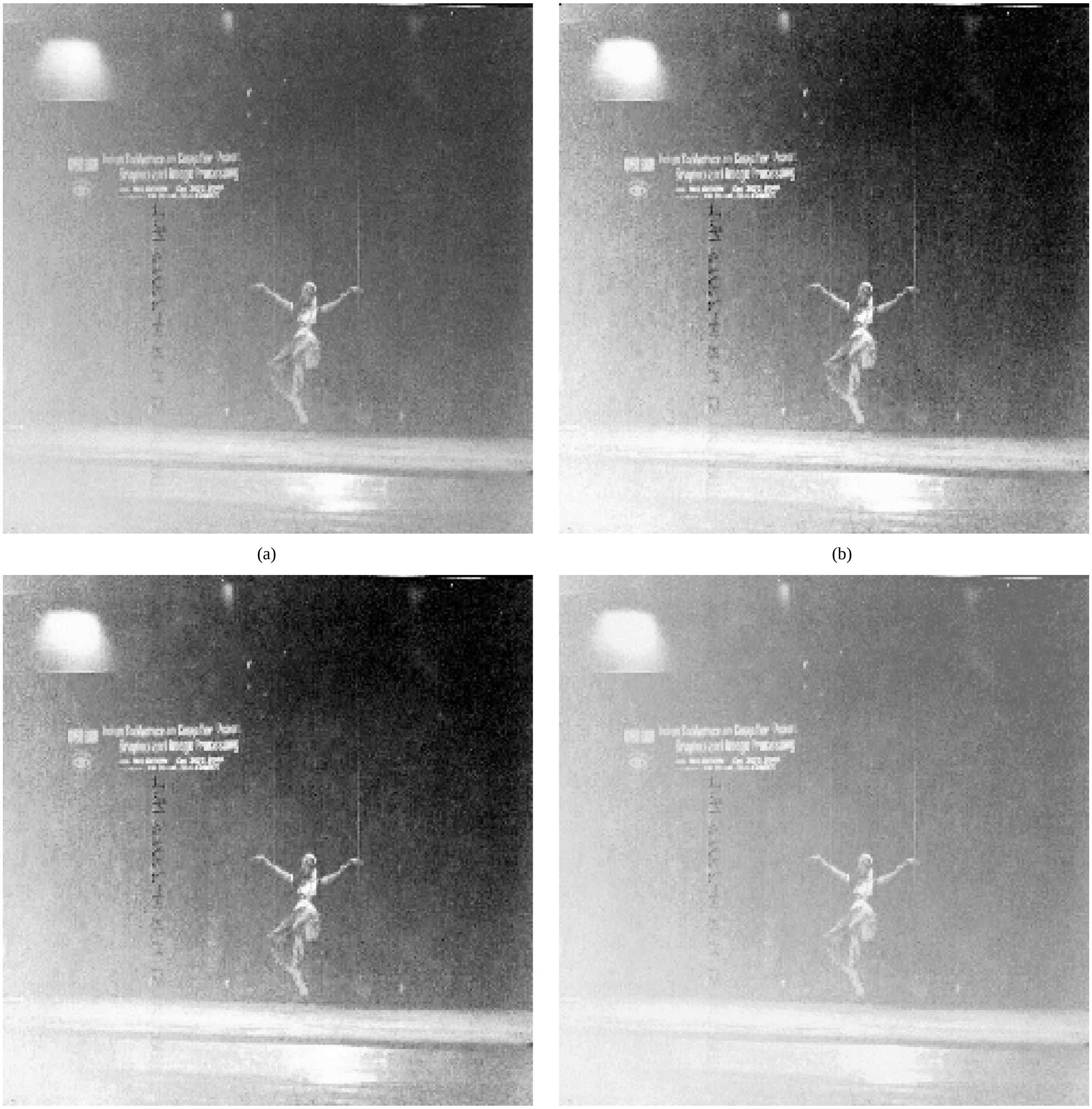
(a) (b) (c) (d)

Fig. 5. Results on Lenna image. (a) S-type enhancement with $n = 2$ and $m = 1.5$, (b) proposed histogram equalization, (c) Yang *et al.*'s method in LHS system, and (d) Weeks *et al.*'s method.

the poor lighting. In the artificial image, there are eight rectangular colored boxes with different hues and different luminance values. Each rectangular box is divided into two square boxes with different saturations but same hue and same luminance values. Figs. 5–7 provide results of applying the proposed methods, Yang *et al.* [20] and Weeks *et al.*'s [18] methods on Lenna, Dancer, and an Artificial image, respectively.

In Strickland *et al.* [3], it is mentioned that objects can exhibit variation in color saturation with little or no corresponding luminance variation. From this fact it can so happen that there can be an edge due to the variation in saturation and having little or no variation in spatial intensity. If such type of pixels are severely effected by clipping then edges may be lost or direction of the edges may be changed, which is certainly against the principles of enhancement. Keeping this fact in mind the artificial image Fig. 3 is created in which different hues with different saturations are shown.

The results from Yang *et al.*'s method and our methods are comparable for Lenna and Dancer images. Note that the effect of clipping is not distinctly visible in these images. Let us examine the artificial image [Fig. 7(c)] enhanced by Yang *et al.*'s method. The edge between the two square boxes in the rectan-



(a) (b)

(c) (d)

Fig. 6. Results on Dancer image. (a) S-type enhancement with $n = 2$ and $m = 1.5$, (b) proposed histogram equalization, (c) Yang *et al.*'s method in LHS system, and (d) Weeks *et al.*'s method.

gular boxes of first column and fourth rectangular box of second column in Fig. 7(c) is lost. This is because of the clipping of saturation component. In the images (a) and (b) of Fig. 7, the edges between the consecutive square boxes are preserved. Note that the proposed method preserves the order of occurrence of intensity. It may also be stated that, visually, edges are not deleted in the enhanced versions of the artificial image, using the proposed histogram equalization method and the S-type function based scheme. Weeks *et al.* have applied normalization to bring back the out of bounds values to within the bounds. Effect of it can be seen that the image (d) in Figs. 5–7 is not as bright as the other images in the respective figures. Equalization of saturation sometimes degrades the quality of the image since it leads to very large saturation values that are not present in the natural scenes [11]. Sometimes, increase in both luminance and saturation cause unnatural color. This can be observed in the case of Lenna image [Fig. 5(d)]. The feathers in the hat of Lenna look different from the original. In the original these have low luminance, thus look black. After the enhancement, with the increase in saturation as well as luminance, the colors of these pixels have been changed. In another image (Peppers image is not shown in the article due to lack of space) it is seen that enhancement

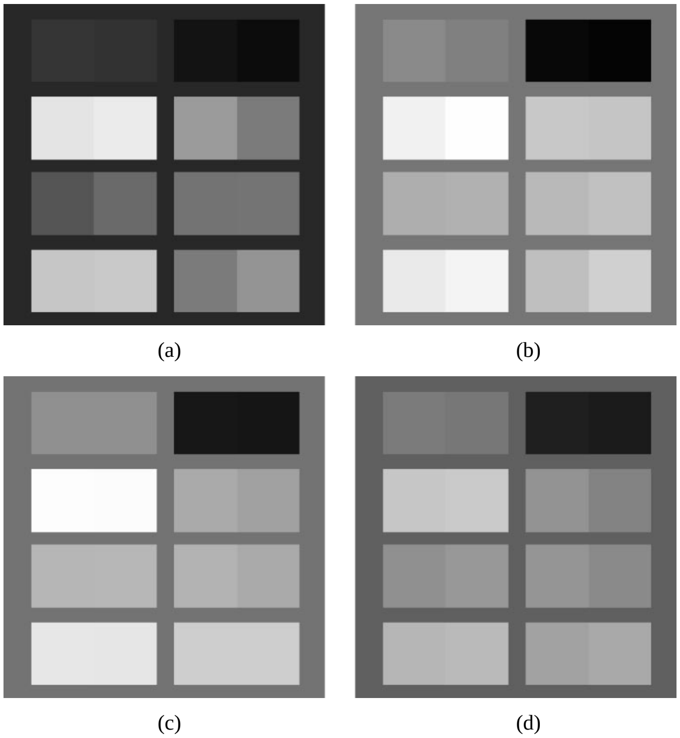


Fig. 7. Results on Artificial image. (a) S-type enhancement with $\mathrm{n} = 2$ and $\mathrm{m} = 1.5$, (b) proposed histogram equalization, (c) Yang *et al.*'s method in LHS system, and (d) Weeks *et al.*'s method.

by this method introduces gray patches. On the other hand the proposed enhancement scheme does not distort the image. The output obtained indicates that the proposed scheme provides acceptable enhancement with all the images. It may be noted that the results of Weeks *et al.*'s method on the artificial image looks better than output of the proposed scheme though the output of the proposed scheme is also an acceptable one.

VI. Conclusion and Discussion

The main contribution here is the scheme to generalize any grey scale image enhancement method to color images without encountering gamut problem. The overall enhancement obtained by the proposed scheme is mainly dependent on the already existing different contrast enhancement functions for grey scale images. These contrast enhancement functions for grey scale images are generalized to enhance the intensity of the color images, keeping the hue intact. A novel scheme is proposed to avoid gamut problem arising during the process of enhancement. This scheme is used to enhance the intensity of color images using a general hue preserving contrast enhancement function. The transformation is general in the sense that the function 'f' can be any contrast enhancement function used for grey scale images and is gamut problem free irrespective of the nature of the function 'f'.

While doing the nonlinear enhancement, we have suggested that linear stretching is to be applied prior to the nonlinear transformation. Here, it may be noted that nonlinear enhancement can also be done independently. The general hue preserving nonlinear transformation is of the form

$$x'_k = \alpha(\tilde{x})x_k + \beta(\tilde{x}).$$

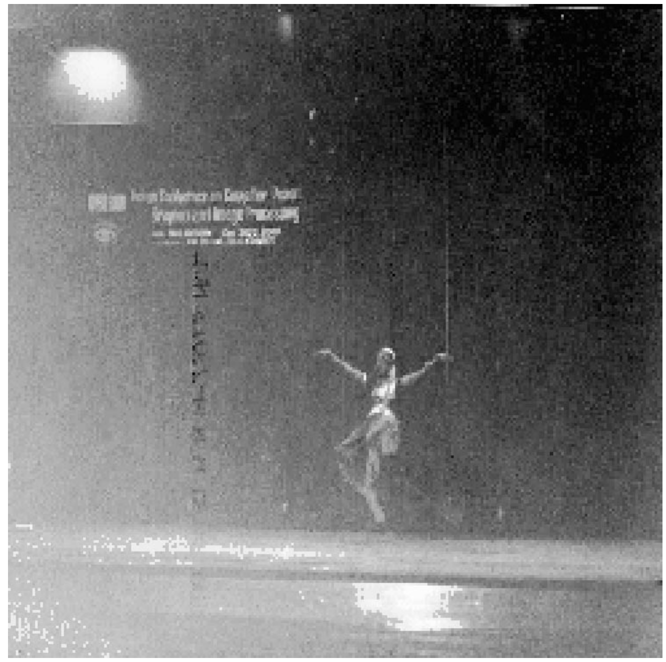


Fig. 8. Equalized by the proposed method without considering the white patches.

The problem here is the choice of the functions $\beta(\tilde{x})$ and $\alpha(\tilde{x})$.

In the theory of proposed histogram equalization method, the maximum possible interval for $\ell_{\tilde{x}}$ is taken to be [0,3]. But sometimes this causes over enhancement. To avoid over enhancement it can be equalized within $[a, b]$ for some $a > 0$ and $b < 3$. In Section V, an example has been provided which shows the over enhancement. In Fig. 7(b), due to this over enhancement, the square box with yellow color becomes almost white, because $\ell_{\tilde{x}}$ of this box is the highest in the image, and after equalization it becomes close to 3 which is almost white.

It is to be noted that, image enhancement is not the panacea of all the problems associated with better visual quality of images. For example, noise in an image will not be removed by contrast enhancement. The proposed histogram equalization technique for color images indeed enhances the image but the clarity of the enhanced image may still be poor in a noisy image [See Figs. 2 and 6(b)]. Note that, in Fig. 2, there are a few bright patches present in it and they dominated the whole enhancement procedure. If the bright patches are removed and the enhancement is performed in the rest of the image then the clarity would be much better. Such an experiment is performed with the help of the proposed histogram equalization method and the result is shown in Fig. 8. The white patches in the image are not considered while equalization is performed. Equalization of $\ell_{\tilde{x}}$ is done in the interval [(1)/(255),2.3]. The visual quality of Fig. 8 is indeed better than the results obtained by all the other methods. For an even better image quality for Dancer image, probably, some noise cleaning algorithm is to be incorporated before enhancement.

The proposed scheme in this article always decreases the saturation whenever it is affected by the condition $\alpha(\ell_{\tilde{x}}) > 1$, which is not always desirable. Some pixels may require to saturate more whereas some may require a decrease in the saturation. This is possible if we consider general nonlinear hue preserving transformation. One needs to be cautious in varying the saturation. The variation should be continuous. Otherwise, it may result in visual artifacts.

Even if $\beta(\tilde{x})$ is zero for all and the linear stretching operation is performed in the original image to increase the length of the interval in each of R, G, and B to the maximum possible extent, $\alpha(\tilde{x})$ need not be a function of $\ell_{\tilde{x}}$. For example, one can take $\alpha(\tilde{x})$ to be a function of $\sqrt{((x_1^2 + x_2^2 + x_3^2)/3)}$, which makes the enhancement function hue preserving. In fact, several other such hue preserving $\alpha(\tilde{x})$ can easily be defined in this way. Construction of generalized nonlinear (both for α and β functions) hue preserving transformation without gamut problem is a matter for future research.

REFERENCES

[1] R. S. Berns, F. W. Billmeyer, and M. Saltzman, *Billmeyer and Saltzman's Principles of Color Technology*, 3rd ed. New York: Wiley, 2000.

[2] G. J. Chamberlin, *The CIE International Color System Explained*. Salisbury, U.K.: Tintometer, 1951.

[3] R. N. Strickland, C. S. Kim, and W. F. McDonnel, "Digital color image enhancement based on the saturation component," *Opt. Eng.*, vol. 26, no. 7, pp. 609–616, 1987.

[4] B. A. Thomas, R. N. Strickland, and J. J. Rodriguez, "Color image enhancement using spatially adaptive saturation feedback," in *Proc. IEEE Int. Conf. on Image Processing*, 1997.

[5] A. Toet, "Multiscale color image enhancement," *Pattern Recognit. Lett.*, vol. 13, pp. 167–174, 1992.

[6] A. R. Gillespie, A. B. Khale, and R. E. Walker, "Color enhancement of highly correlated images. I. Decorrelation and HSI contrast stretches," *Remote Sens. Of Environ.*, vol. 20, no. 3, pp. 209–235, 1986.

[7] ——, "Color enhancement of highly correlated images. II. Channel ratio and "chromaticity" transformation techniques," *Remote Sensing Of Environment*, vol. 22, pp. 343–365, 1987.

[8] A. Gupta and B. Chanda, "A hue preserving enhancement scheme for a class of color images," *Pattern Recognit. Lett.*, vol. 17, pp. 109–114, 1996.

[9] M.-S. Shyu and J.-J. Leou, "A genetic algorithm approach to color image enhancement," *Pattern Recognit.*, vol. 31, no. 7, pp. 871–880, Jul. 1998.

[10] L. Lucchese, S. K. Mitra, and J. Mukherjee, "A new algorithm based on saturation and desaturation in the xy-chromaticity diagram for enhancement and re-rendition of color images," *Proc. IEEE Int. Conf. on Image Processing*, pp. 1077–1080, 2001.

[11] I. Pitas and P. Kinikilis, "Multichannel techniques in color image enhancement and modeling," *IEEE Trans. Image Processing*, vol. 5, no. 1, pp. 168–171, January 1996.

[12] V. Buzuloiu, M. Ciuc, R. M. Rangayyan, and C. Vertan, "Adaptive-neighborhood histogram equalization of color images," *J. Electron. Imag.*, vol. 10, no. 2, pp. 445–459, 2001.

[13] P. E. Trahanias and A. N. Venetsanopoulos, "Color image enhancement through 3-D histogram equalization," in *Proc. 15th IAPR Int. Conf. Pattern Recognition*, vol. 1, 1992, pp. 545–548.

[14] P. A. Mlsna and J. J. Rodriguez, "A multivariate contrast enhancement technique for multispectral images," *IEEE Trans. Geosci. Remote Sensing*, vol. 33, no. 1, pp. 212–216, 1995.

[15] P. A. Mlsna, Q. Zhang, and J. J. Rodriguez, "3-D histogram modification of color images," *Proc. IEEE Intl. Conf. Image Processing*, vol. III, pp. 1015–1018, 1996.

[16] Q. Zhang, P. A. Mlsna, and J. J. Rodriguez, "A recursive technique for 3-D histogram enhancement of color images," *Proc. IEEE Southwest Symp. on Image Analysis and Interpretation*, pp. 218–223, 1996.

[17] I. M. Bockstein, "Color equalization method and its application to color image processing," *J. Opt. Soc. Amer.*, vol. 3, no. 5, pp. 735–737, 1986.

[18] A. R. Weeks, G. E. Hague, and H. R. Myler, "Histogram specification of 24-bit color images in the color difference (C-Y) color space," *J. Electron. Imag.*, vol. 4, no. 1, pp. 15–22, 1995.

[19] C. C. Yang and J. J. Rodriguez, "Efficient luminance and saturation processing techniques for bypassing color coordinate transformations," in *Proc. IEEE Int. Conf. on Systems, Man, and Cybernetics*, vol. 1, 1995, pp. 667–672.

[20] ——, "Saturation clipping in the LHS and YIQ color spaces," in *Proc. IS&T/SPIE Int. Symp. Electronic Imaging: Science & Technology – Color Imaging: Device-Independent Color, Color Hard Copy, and Graphic Arts*, San Jose, CA, 1996.

[21] J. J. Rodriguez and C. C. Yang, "High-resolution histogram modification of color images," *Graph. Models Image Process*, vol. 57, no. 5, pp. 432–440, 1995.

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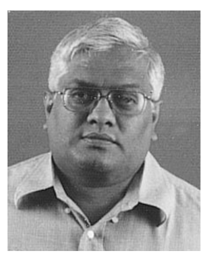

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