

*“A Picture of many colors proclaims images of many Thoughts.” ~ Donna A. Favors (Member of the Board of Directors of the Montgomery Institute, 1955)*

## Chapter 4

### METHODS FOR COLOR AND CONTRAST ENHANCEMENT IN IMAGES AND VIDEO

The goal of color and contrast enhancement in general is to provide a more appealing image or video with vivid colors and clarity of details. These enhancements are intimately related to different attributes of visual sensation. It is important to define these attributes before discussing the objectives of color and contrast enhancement, or the various methods to achieve them.

Perceptual Attribute	Definition
Brightness	Attribute of a visual sensation according to which an area appears to emit more or less light. [Fairchild 2005]
Lightness	Attribute of a visual perception by which a perceived color is judged to be equivalent to one of a series of grays ranging from black to white. [Berns 2000] In other words, it is the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting. [Fairchild 2005]
Hue	Attribute of a visual perception according to which an area appears to be similar to one of the colors, red, yellow, green, and blue, or to a combination of adjacent pairs of these colors considered in a closed ring. [Berns 2000]
Colorfulness	Attribute of a visual perception according to which an area appears to exhibit more or less of its hue. [Hunt 2001]
Chroma	Colorfulness of an area judged in proportion to the brightness of a similarly illuminated area that appears to be white or highly transmitting. [Hunt 2001]
Saturation	Colorfulness of an area judged in proportion to its brightness. [Hunt 2001] By definition, saturation = chroma/lightness.

The objective of contrast enhancement is to increase the visibility of details that may be obscured by deficient global and local lightness. The goal of color enhancement can be either to increase the colorfulness, or to increase the saturation. Increasing the lightness can give a perception of increased colorfulness, however in this case perceived saturation reduces for a given chroma. On the other hand, perceived saturation can be increased by increasing chroma or reducing lightness, or both. If chroma is increased moderately while slightly reducing the lightness, both saturation and colorfulness in an image can be enhanced. This method is also likely to avoid out-of-gamut or unrealizable colors.

The next section discusses several previously published methods for color and contrast enhancement that served as a preamble for the current research. Then, the development of the new algorithm is discussed in detail, starting with the working requirement, the color space chosen for the development, a detailed description of the three key components of the algorithm, and finally the innovation that was achieved in this work.

#### **4.1 Color and Contrast Enhancement in Digital Images: A Review of Past Research**

Most of the published works to date focus on color enhancement in digital color images. Many of these techniques can theoretically be implemented for video as well. However, hardware implementation issues can impose serious restrictions for many of these techniques. These issues have not been considered in this discussion. Also note that the methods discussed here do not involve signal processing as much as image processing. Image enhancement methods relying on signal processing do not involve a great deal of perceptual processing that will be considered

appropriate from color science standpoint. [de Haan 2003] A brief overview of such methods is included in Chapter 2.

#### **4.1.1 Color Processing in LHS Space**

In the early '80s, as color images and video media started getting increasingly commonplace, researchers soon realized that most of the enhancement techniques developed for monochrome images led to artifacts when applied to color images. In one of the earliest papers on color enhancement, Strickland, Kim and McDonnell [Strickland 1986, Strickland 1987] recognized that RGB color space did not correspond with the human color perception and so, image enhancement algorithms applied directly to RGB images could lead to color artifacts. They suggested performing enhancement operations in a color space whose dimension corresponded to luminance, hue and saturation. The authors also pointed out that enhancing luminance alone could lead to color artifacts in low luminance regions, and thus simultaneous saturation processing was required for proper enhancement. They presented the derivation of LHS coordinates from RGB. Because of the nonlinear transformation between the two color spaces, some processed colors were at risk of being out-of-gamut when converted back to RGB. Strickland, Kim and McDonnell proposed to clip the RGB pixel vector at the color cube boundary to prevent color shift during the clipping operation.

#### **4.1.2 Histogram Based Methods**

Histogram equalization is a common approach for enhancing contrast and brightness in grayscale images. Extending this tool to color images is not straightforward. Color histogram equalization is a three-dimensional problem. Moreover, RGB is not a suitable color space because of its poor

correlation with human visual system, requiring a color space transformation. Histogram equalization on the intensity component can improve the contrast, but can cause de-saturation in areas where histogram equalization results in a large reduction in intensity. Similarly, equalization of the saturation component alone can lead to color artifacts. Independent equalization of RGB components is also not advisable as it can lead to a hue shift. In one of the earliest papers on color processing in color difference space (YCC), Hague, Weeks and Myler [Hague 1994] presented an approach where histogram equalization was performed on saturation for each hue in the image, taking into account the maximum allowable saturation for a given luminance. The color space was segmented into various pie-shaped hue regions, each of which was further divided into several luminance regions, as shown in Figure 4.1. For each of these regions, the minimum possible saturation value was zero, while the maximum possible saturation value was a function of both hue and luminance. Maximum allowable saturation for each region was determined by computing the saturation for every RGB combination and retaining the largest value computed within each hue region for all different luminance regions. Once the saturation limits were determined, histogram equalization was applied to each of the luminance regions within each hue region. Saturation equalization was followed by luminance equalization over the entire luminance image. This method helped reduce the number of out-of-gamut colors as well as color artifacts.

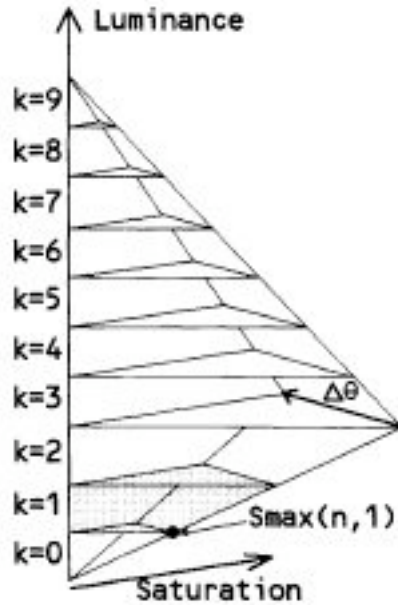


Fig. 4.1 A single C-Y hue region, divided into different luminance regions [Hague 1994, Fig. 4]

The main limitation of the above method, or of any histogram dependent processing for that matter, is that it is a global method and has little control over local contrast. It does not take into account the content of input images. The other critical disadvantage is that this and other histogram based methods do not consider the perceptual aspects of human visual system. As a result, a change in the lightness and saturation of a given pixel or region may or may not be perceived as a desirable effect.

Weeks, Sartor and Myler [Weeks 1999] extended Hague, Weeks and Myler's histogram equalization approach by using histogram specification for color image enhancement in color difference space. In this method desired hue, saturation and luminance histograms were specified separately, but the correlation between different components were also taken into account. An advantage to this approach was that the saturation component could be enhanced while leaving

hue and luminance unchanged. Saturation distribution nevertheless was a function of luminance and hue, since maximum saturation was a function of these two components. Sixty-four luminance regions and sixteen hue regions were considered. A 64x16 array stored the maximum saturation value for each region. Sixteen saturation histograms were specified for each hue region, and within each hue region 64 specified histograms were generated, scaling each of those by the maximum saturation for the given luminance/hue region. In other words, saturation histograms for different luminance regions under a given hue region had the same shape, but different widths due to varying maximum saturation as a function of luminance. Best performance was achieved by first equalizing the luminance component and then redistributing the saturation component across complimentary hue regions according to a Gaussian distribution. Figure 4.2 shows the input specified histogram for one of the test images used in Hague, Weeks and Myler's work [**Hague 1994**] and the resulting saturation histogram for a single intensity/hue region in the enhanced image.

Although this method performed better than histogram equalization in enhancing the image and reducing color artifacts and hue noise, this method was not fully automatic since different histogram specifications had to be adopted for different images.

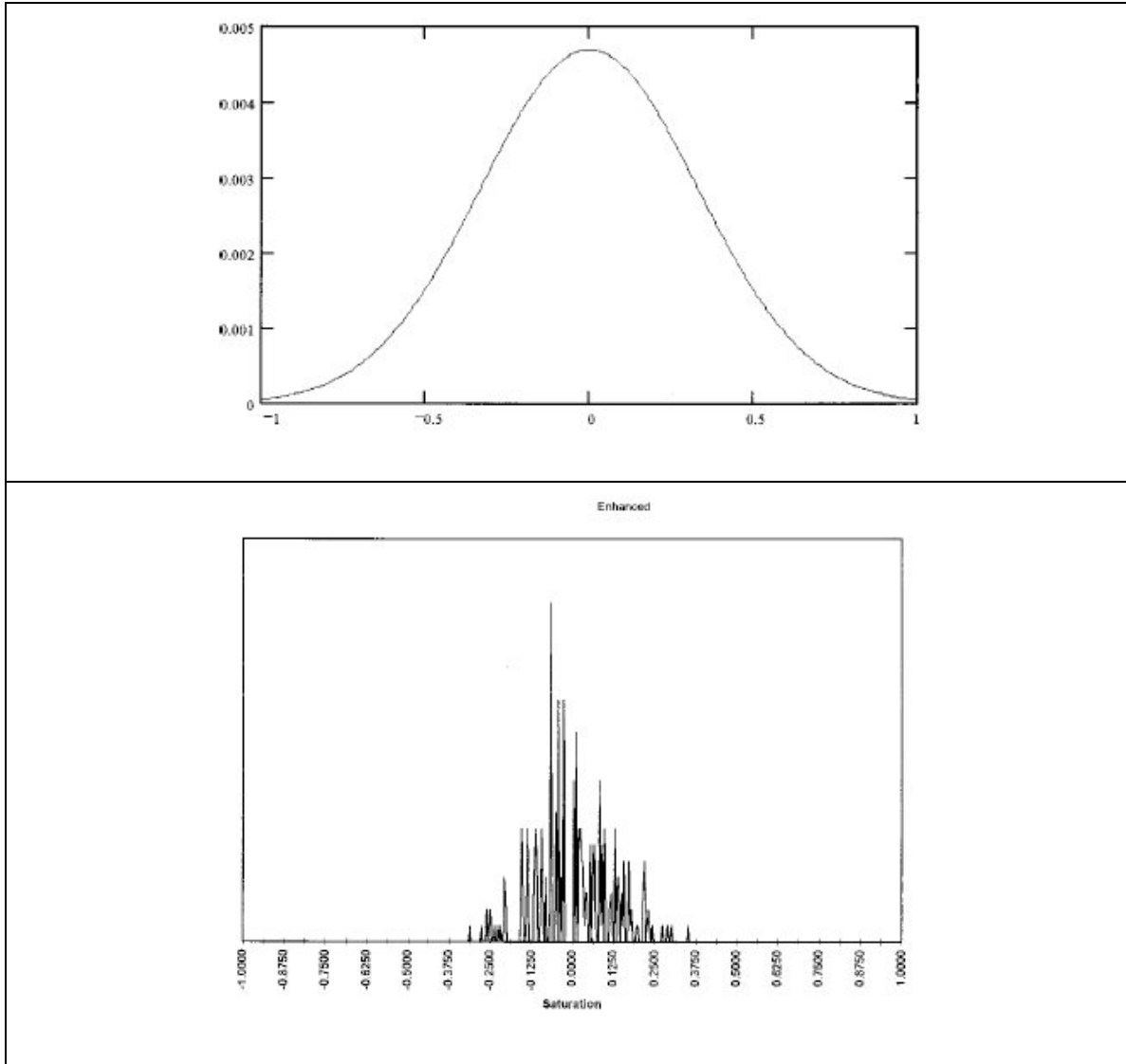


Fig. 4.2 Specified histogram saturation for one of the test images (top) and the saturation histogram for a single intensity/hue region in the saturation enhanced image [Weeks 1999, Fig. 9 and 12]

#### 4.1.3 Color/Contrast Enhancement Method Based on the Chromaticity Diagram

In a different approach, Lucchese, Mitra and Mukherjee [Lucchese 2001] presented a two-stage method for color contrast enhancement based on xy chromaticity diagram. All colors with positive chroma values were maximally saturated through shifting to the borders of a given color gamut. In the next stage, the colors were desaturated toward a new white point by an appropriate

color-mixing rule. Lucchese et al's method is shown in Figure 4.3. RGB coordinates define the color gamut.  $W$  is the white point. Saturation of any color  $C_1$  is enhanced by moving the point along the straight line joining  $W$  and  $C_1$  to the point  $S$  on the spectrum locus. Next, a color mixing law is used to desaturate  $S$  and compute coordinates for the final color  $C_2$ .

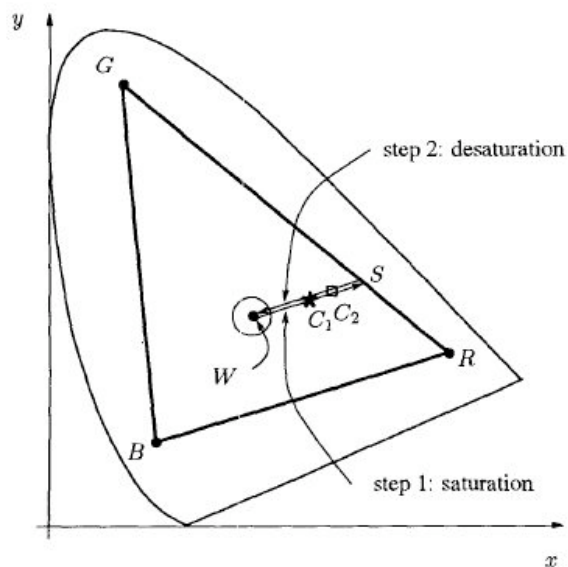


Fig. 4.3 Color enhancement using chromaticity diagram ( $C_1$  and  $C_2$  are color coordinates before and after enhancement) [Lucchese 2001, Fig. 1]

The method described above suffers from a serious flaw. Chromaticity diagram does not represent a perceptual space. Thus, a straight line joining the white point and a given point in the color gamut on the chromaticity diagram is unlikely to preserve constancy of perceived hue.

In yet another attempt to develop an image enhancement method based on the chromaticity diagram, Colantoni, Bost and Trémeau [Colantoni 2004] used  $\lambda SY$  color space for colorfulness enhancement. This space is derived from  $xyY$  color space and is based on the dominant

wavelength ( $\lambda$ ), saturation (S) and intensity (Y). Figure 4.4 describes the idea. Any real color  $x$  lying within the region enclosed by the spectrum locus and the lines BW and RW can be considered to be a mixture of the white point chromaticities and those of the spectrum light of the dominant wavelength ( $\lambda_d$ ). The dominant wavelength is obtained by extending the line WX until it intersects the spectrum locus. The color triangle defines the device gamut.

Four methods were developed to increase the saturation of the color of each pixel in the direction of dominant wavelength, thereby enhancing the colorfulness of images. In the first method, the original saturation was increased by different fractions. In the second method, the saturation component was increased to the maximum saturation, which was a function of both hue and luminance. This method was found to greatly increase color contrast at the cost of perceptual quality. The third method reduced the luminance component by a given fraction and then increased the saturation component in the same way as the first method. In the last method, fractional luminance reduction was followed by increasing the saturation component to the maximum saturation corresponding to the adjusted luminance.

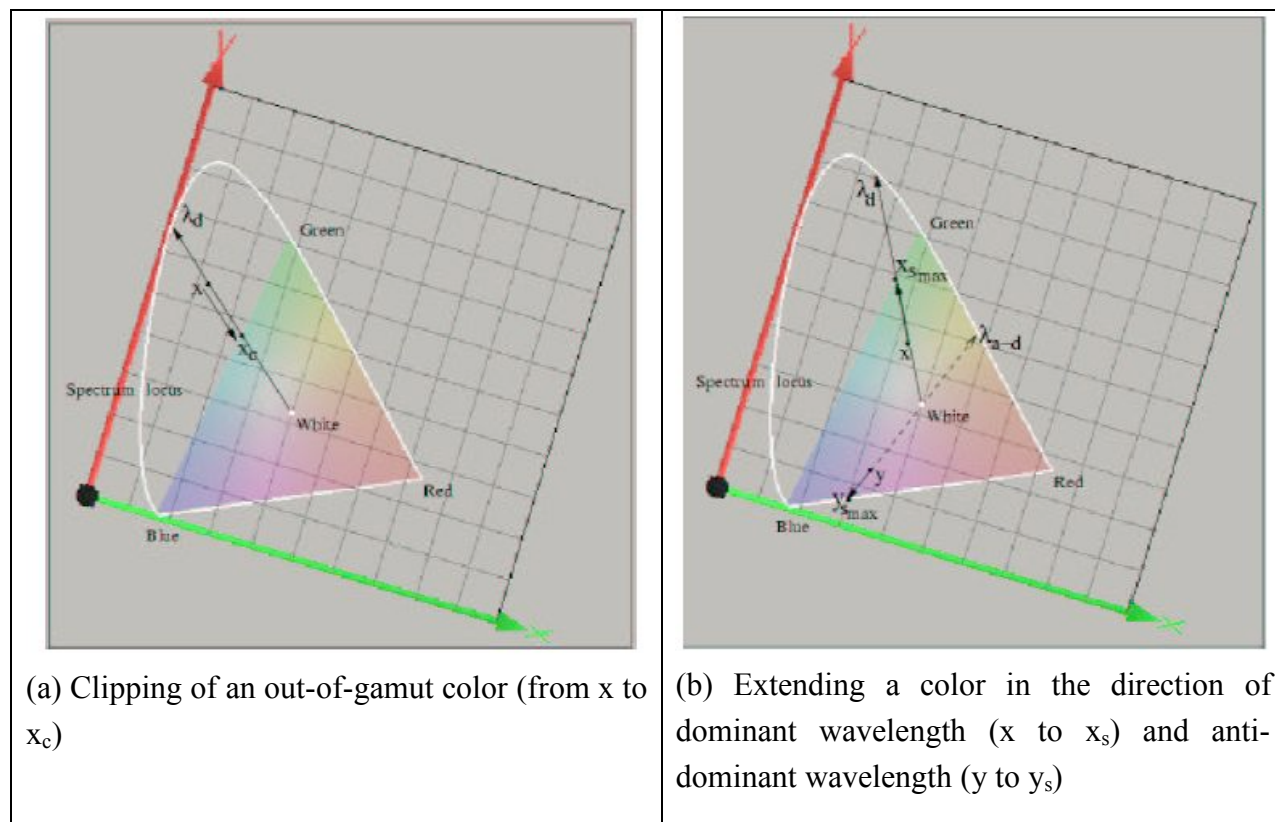


Fig. 4.4 Color enhancement in  $\lambda SY$  color space [Colantoni 2004, Fig. 1]

The authors found a weak dependence between image content and chroma and lightness changes. Very strong colorfulness enhancement resulted in poor image quality. Also, increased saturation was found to introduce hue noise in uniform areas and background.

While this method is fast and inexpensive,  $\lambda SY$  is by no means a perceptual color space. The above method is likely to result in a hue shift since it ignores the fact that constant hue lines are curvilinear in a chromaticity diagram. The perceived hue shift will depend on the amount of saturation enhancement. Further, an equal amount of change in the chromaticities in different regions of the diagram will lead to a different amount of perceptual color difference.

#### 4.1.4 Saturation Clipping in LHS and YIQ Color Space

As already discussed, since RGB color space does not conform to human perception of color, many a time color processing is done by first transforming RGB image to a new color space, and converting it back to RGB once the processing is complete. However, due to the fact that the useful range of saturation decreases as one moves away from the medium luminance values, upon conversion back to RGB, it is possible to end up with illegal (out of gamut) colors. One solution is to clip the processed luminance value before transforming back to RGB, but this can lead to artifacts such as bright spots, washout regions, and loss of local contrast at the end regions of the range since many pixels can be clipped to the same luminance.

Yang and Rodriguez proposed a hue-preserving graphical approach involving scaling and shifting that bypassed computationally intensive coordinate transformation during color image processing [Yang 1995]. This method was intended for cases where only the luminance or only the saturation component needed to be modified. Later, the same authors proposed a method where the saturation of an out-of-gamut color was clipped, instead of luminance [Yang 1996]. This method was implemented in LHS and YIQ (formulated by NTSC) color spaces. The method is depicted in Figure 4 (a). The luminance of a pixel with saturation  $S$  changes from  $L$  to  $L'$  after processing. The point  $(L',S)$  will map to outside the RGB gamut, so it needs clipping. The point can be clipped to  $(L'',S)$  by reducing the luminance, but may lead to reduced perceived contrast. Alternately, the saturation of the point  $(L',S)$  can be reduced to obtain the point  $(L',S')$ , which will also map to an in-gamut RGB value. Similar processing can be performed in YIQ space, as shown in Figure 4.5 (b).

Saturation clipping resulted in improved contrast compared to the results obtained from luminance clipping. However, this method is intended for applications where only the lightness is being enhanced.

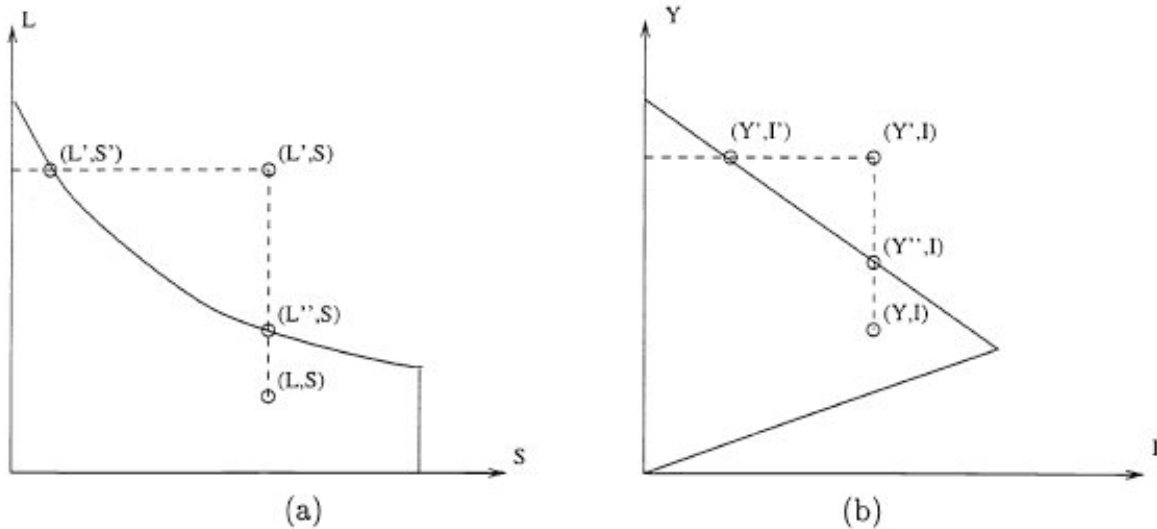


Fig. 4.5 Saturation clipping for red hue plane in (a) LHS and (b) YIQ [Yang 2006, Fig. 4]

#### 4.1.5 Retinex-Based Image Enhancement Methods

In one of the significant contributions, Edwin Land conceived the retinex theory to model visual perception of lightness and human vision color constancy [Land 1983, Land 1986]. The theory was formulated based on the experimental demonstrations that color appearance was controlled by surface reflectances and spatial distribution of colors in a scene rather than the spectral properties of reflected light. In its most recent form, the concept evolved into a center/surround spatially opponent operation related to neurophysiological functions. Proposed mechanisms were thought to be a combination of retinal and cortical mechanisms. The color of a unit area was determined by a trio of lightness numbers corresponding to three single wavebands, long, middle

and short. The numbers together represented the relationship between the unit area and the rest of the unit areas in the scene. The output for a given waveband was determined by taking the ratio of the signal at any given point in the scene and normalizing it with an average of the signals for that waveband throughout the scene. Thus, retinex theory acknowledged the influence of background in determining the color of the stimulus [Fairchild 2005]. Even though the retinex model has some weaknesses in physiological modeling, retinex theory has been widely used in various application areas, including image enhancement.

Meylan and Süsstrunk [Meylan 2004] proposed a retinex-based method for high dynamic range rendering of natural images. At first, a global tone mapping was applied on the linear image. Luminance component was then computed from the non-linear RGB image. An adaptive filter algorithm based on retinex was applied to luminance data. Then, the modified luminance and original chrominance components were transformed back to RGB. Finally, the RGB image was scaled to the output device dynamic range using histogram scaling. The key feature of the low-pass retinex-based filter was that the surround function was not circularly symmetric, but followed the image's high contrast edges. The filter coefficients were determined by traversing the surround radially for each rotation angle. Further, the radial one-dimensional function was a Gaussian curve with spatial constant varying with the local contrast. The method reduced artifacts like black halos around light sources, but the processing time increased significantly.

Hsu and others [Hsu 2006] used non-isotropic Gaussian kernel filters in a multiple-scale retinex method. The logarithmic intensity of the image was subjected to a low-pass Gaussian filter with adaptive width, following which weighted multi-scale retinex ratios were computed. Chromatic

information from the input image was used to restore color, and then luminance histogram equalization was performed to enhance image contrast. Retinex ratios and equalized intensities were multiplied to get the final output. The authors reported better local contrast and rendering effects than previously published methods.

Rahman, Jobson and Woodell focused on multi-scale retinex based approach for color image enhancement [**Rahman 1996, Rahman 2004**]. Main goals were to achieve an image rendering close to the original scene, and to increase the local contrast in dark regions of high dynamic range scenes. In order to achieve a balance between the dynamic range compression and tone mapping, multiple-scale surround with Gaussian distribution was used. A color restoration method was proposed to compensate for the desaturation effect inherent in retinex-based methods due to non-conformity to gray world assumption both globally and locally. Color restoration took the form of a logarithmic spectral computation. However, color restoration was found to be inadequate for preserving the saturation of the lighter colors, and thus a white balance process was introduced to address this issue.

In a different approach, Choi et al [**Choi 2007**] proposed a color image enhancement method based on the single-scale retinex with a just noticeable difference (JND)-based nonlinear filter. The processing was done in the HSV color space. Only S and V components were enhanced, and original hue was maintained. To enhance the V component, the illumination was first estimated using the JND-based filter. A fraction of the logarithm of the estimated illumination was subtracted from the logarithm of the input V component, which was followed by histogram modeling to obtain output V component. The S component of the image was enhanced in equal

proportion as the V component. Finally, RGB output image was computed from the output HSV image. The results were found to be superior than conventional histogram equalization and standard single-scale retinex methods.

For any color enhancement method based on retinex theory, the main weakness lies in the fact that no direct interdependence is assumed between the luminance and chrominance data. Even though methods like color restoration described above were proposed as an extension, it is very difficult to maintain the relationship between lightness and chroma. Note that nonlinear processing is performed on the luminance data in a color space where luminance and chrominance data are not necessarily decoupled. Algorithms based on retinex theory are in many ways simply lightness adjustment and/or local contrast enhancement algorithms. Further, retinex-based methods are computationally expensive, making them difficult to implement in commercial imaging devices.

#### **4.1.6 Geometrical Method for Lightness Adjustment**

Samadani and Li [Samadani 2006] proposed a method for lightness adjustment that was motivated by the fact that the color of an object of uniform material varies along a luminance-saturation curve as the intensity and the angle of the light source changes. Their approach focuses on lightening or darkening of an image where colors are directly adjusted by moving them along lightness-saturation curves (Figure 4.6) while leaving the hue unchanged. In the simplified version of the method, for each hue, the saturation is assumed a separable function of luminance and a scale parameter (Figure 4.7). The maximum saturation point determines the shape of the curve, which is a function of luminance, and implicitly, of hue. Curves can be stored

as Lookup Tables for three primary and three secondary hues, and saturation value corresponding to an intermediate hue can be obtained through interpolation. All processing is done in the YCC space. The authors compared the results with that of a standard algorithm where only the luminance was processed and out-of-gamut colors were clipped to the boundary. Samadani and Li's method offered improved clipping and avoided excessive or insufficient saturation of pixels.

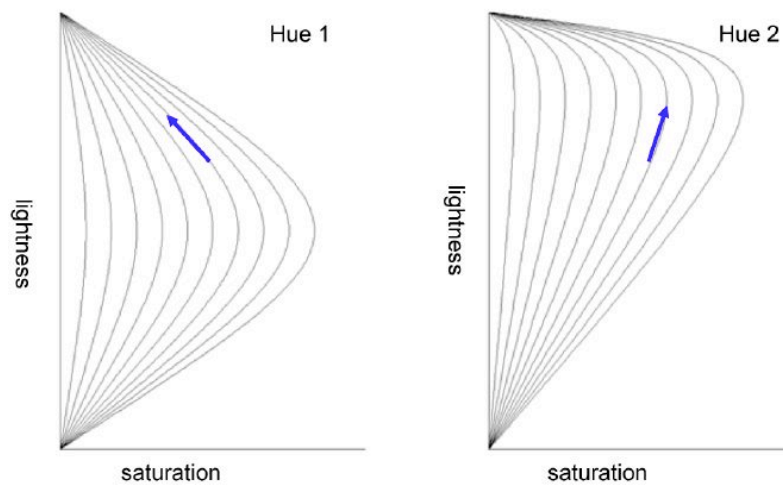


Fig. 4.6 Saturation-lightness curve families for two different hues [Samadani 2006, Fig. 2]

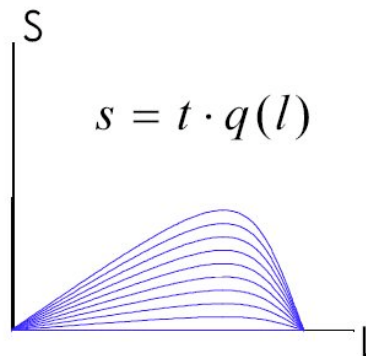


Fig. 4.7 Saturation as a separable function of luminance [Samadani 2006, Fig. 4]

#### **4.1.7 AINDANE: Locally Adaptive Image Enhancement**

Tao and Asari [Tao 2004] proposed a nonlinear image enhancement method called AINDANE (adaptive and integrated neighborhood dependent approach for nonlinear enhancement). This algorithm specifically addresses visual quality issues of digital images captured under low or non-uniform illumination conditions. The algorithm involves two independent processes, adaptive luminance enhancement for dynamic range compression and adaptive contrast enhancement to preserve visual details, followed by the tone reproduction of the original image. In the adaptive luminance enhancement, the intensity values are subject to a nonlinear transfer function, shown in Fig. 4.8 (a), which also serves as dynamic range compression as the intensities of darker pixels are increased. One of the parameters in the transfer function is the intensity corresponding to the cumulative distribution function (CDF) of 0.1. As a result, the luminance enhancement depends on the lightness of the original image. Intensity of darker pixels are increased significantly, while pixels with sufficient intensity remain unchanged.

In the following stage, the local contrast enhancement is achieved by taking into account the intensities of surrounding pixels by using a 2D discrete spatial convolution with a Gaussian kernel. The luminance-enhanced image is subject to an exponential, which is an expression of the ratio of convolved intensity and the original intensity. This exponential in turn is raised to the power of a function of the global standard deviation. The transfer function is shown in Fig. 4.8(b). Once the adaptive contrast enhancement is complete, a linear color restoration process is performed based on the chromatic information contained in the input image.

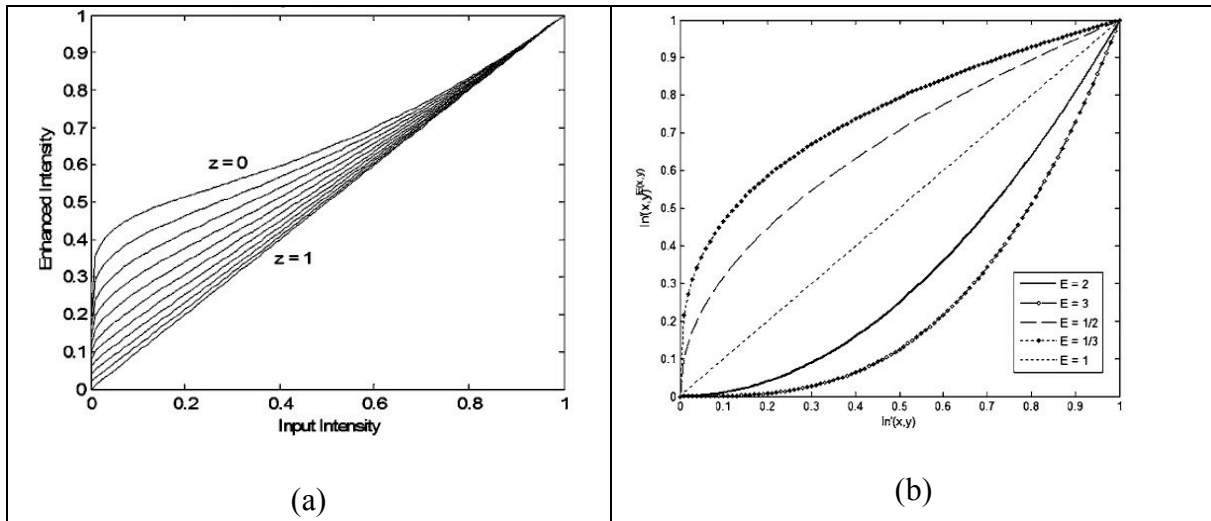


Fig. 4.8 Nonlinear transfer functions for (a) adaptive luminance enhancement and (b) adaptive contrast enhancement [Tao 2004, Fig. 3 and 4]

Tao and Asari's method suffers from a major technical flaw in the final stage. The assumption that the relationship between the RGB channel values will be maintained even after several nonlinear processing is fundamentally wrong. This also requires a manual adjustment of the color correction operation. However, the adaptive luminance enhancement process was reported to produce superior results compared to other published methods. The global lightness adjustment method proposed in the present research has been partly inspired by Tao and Asari's method.

#### 4.1.8 Sigmoidal Lightness Rescaling Function

Braun and Fairchild [Braun 1999] proposed sigmoidal lightness rescaling function to maintain the perceived lightness contrast that selectively rescaled images from a source device with a full dynamic range into a destination device with a limited dynamic range. This achieved the effect of enhancing the overall contrast by increasing the lightness difference between the highlight and

shadow regions. This method, essentially developed for color gamut mapping of pictorial images, uses lightness remapping based on the phenomenon of simultaneous lightness contrast. The highlights are lightened and the shadowed regions are darkened, thus increasing the image contrast. However, this strategy was not found to be suitable for the purpose of color enhancement. Increasing the lightness of lighter colors did not leave much room for increasing the saturation in the following step, resulting in increased clipping. Further, reducing intensity of the low-intensity pixels resulted in loss of details in darker parts of an input image.

#### **4.1.9 Local Color Correction Using Nonlinear Masking**

When a high dynamic range image has to be reproduced in lower dynamic range displays or other output devices, it becomes difficult to design a global tone reproduction that will accommodate both shadow and highlight detail. Moroney [Moroney 2000] presented a local color correction operation based on nonlinear masking. The method is equivalent to deriving a specific tone reproduction curve for each pixel in the image. In this method, one input value can be mapped to many output values, depending on the values of the neighboring pixels. At first, an image mask is derived from an inverted low-pass filtered image, which is then combined with the input image. The combination operator consists of a simple power function.

Moroney's method did not produce desirable results in our case, understandably because of different working requirements. Lightening the dark regions and darkening the light regions by themselves are not appropriate strategies for color and contrast enhancement. The results were not as satisfactory as with the new method described in Section 4.2.

#### **4.1.10 Patented Methods for Color Processing in Images and Video**

Many color and contrast enhancement methods developed in the industry can be found not in the publications, but in various patents. A preliminary search of US patent database was conducted as part of this research. This section discusses several approved or pending US patents that are relevant to color image or video enhancement.

Lightness increase in an image often leads to a reduction in the saturation, and lightness reduction often results in saturation increase. A patent filed by Hermann Fuchsberger of AGFA [US Patent 4,831,434] offered a simple method for the correction of color saturation by taking the ratio of the luminance signals before and after luminance processing and multiplying their quotient by each of the two chrominance signals. Mainly YCC color space, quite common in the video processing area, was considered in this method. This color saturation correction method was suitable for photographic applications, where maintaining the original color saturation during contrast enhancement was of interest. The fundamental drawback of this method was that it did not take into account the fact that lightness and chroma were not linearly related in a perceptual space. A 10% increase in the luminance signal does not translate to a 10% increase in the color saturation. The respective change in the two chrominance channel signals are also likely to be different.

Bachmann et al [US Patent 5282021] invented a method for color correction of a video signal and implemented in the hardware. It is assumed that the video signal is separated into luminance and chrominance information, as in YCC color space. Hue and saturation are computed from the

chrominance or color difference data and converted into polar coordinates. The method involves specifying six overlapping triangular color sectors, where any hue lying in the overlapped regions of two sectors has specific control values corresponding to the two overlapping sectors. These sectors overlap by half of their angular magnitude of the sectors. Thus, the degree of the correction is stored as a function of hue. Based on the control values, corrections for the input hue, saturation and luminance are determined. A color sector manual selection unit enables manual correction of hue, saturation and luminance through a common keyboard interface. An additional signal correlated to the color hue sectors is generated. The two control values and the additional signal value are used to compute the corrected hue, saturation and luminance values. Hue correction is additive while saturation and luminance corrections are multiplicative. In the final step, the corrected hue, saturation and luminance were converted into the color difference data. The main idea behind the concept was to prevent the saturation correction leading to an illegal hue, as well as to prevent a hue correction from changing the saturation of those colors that do not correspond to the given input hue.

Jeong et al implemented a color image enhancement method for video display where sharpness was improved using the saturation component obtained by converting RGB image data into LHS values [US Patent 6028646]. Figure 4.9 illustrates the method in a block diagram. The RGB/saturation conversion section normalizes the input RGB image and computes the saturation. The memory section 102 stores the negative image of the saturation. The saturation enhancement section receives this negative image and performs a high-frequency-emphasized filtering with a two-dimensional convolution. The minimum color signal determining section detects the minimum value among the normalized RGB primary color components and

accordingly provides a switching control signal to the switching section 105, which then routes the minimum enhanced primary color component to one of the three different paths in the saturation/RGB conversion section 107. In this section, the negative saturation image is first converted into a positive one before performing enhancement. For example, if the minimum primary color signal is R, the enhanced R component is achieved by multiplying the sum of the original RGB components by the enhanced saturation component, while keeping G and B constant. The other two cases are similar. Delay 107 is to delay the operation of the two conversion sections. The block diagram also contains an optional luminance enhancement section that enhances the Y component in the LHS space obtained from the saturation enhanced image, using the high-frequency-emphasis filter described before and then converts the enhanced data back to RGB.

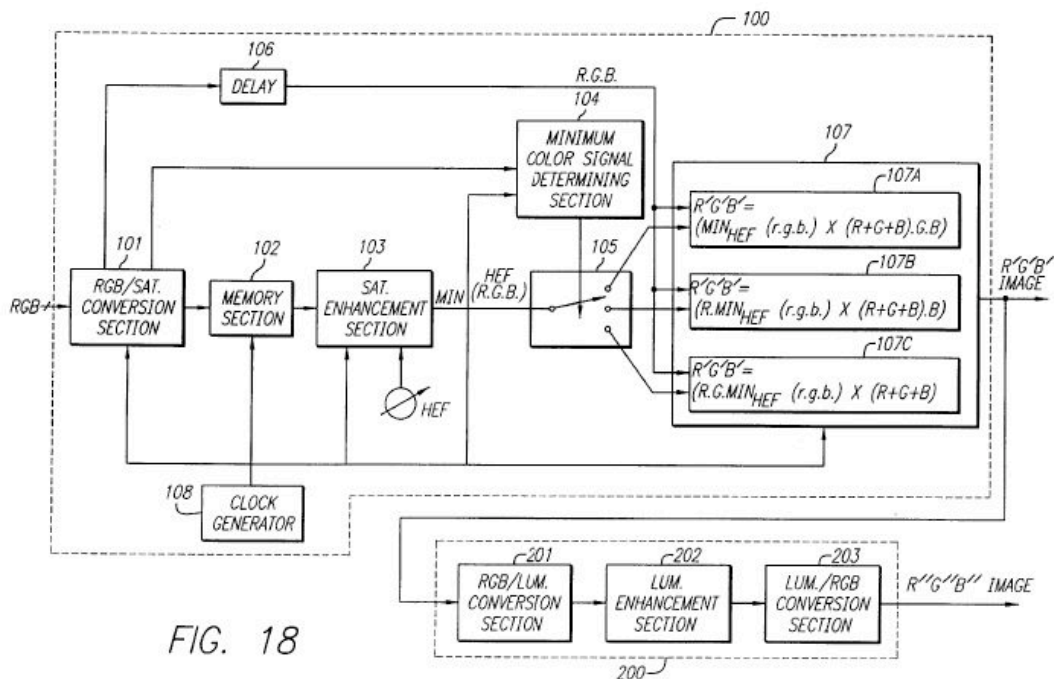


FIG. 18

Fig. 4.9 Color image enhancement device patented by Jeong et al.

Chou developed a method for automatically adjusting, correcting and enhancing the color hue and saturation of each pixel from a color video source [US Patent 2006/0238655]. At first, hue and saturation values are computed from input color difference values in the YCC format. Hue and saturation correction values for a given pixel are determined using lookup tables predetermined for various color tone regions. The hue and saturation adjustments are applied directly to the original chrominance data of the pixel. A separate region control lookup table is used to determine the color tone region in which an input hue falls. The region control output determines the saturation lookup table to be used in the enhancement. A fade module also receives the region control output and fades out the saturation adjustment value obtained from the given saturation lookup table to smoothen the effect of color enhancement for input colors falling at the boundaries of color tone regions, and thus avoid contouring effects.

Wang invented a method to perform color enhancement of an image in a specific color space region [US Patent 2007/0070369 A1]. The block diagram is shown in Figure 4.10. The image in original color space (RGB, CMY, HSI, YIQ etc) is first converted to YUV color space. The color space is partitioned into five regions corresponding to blue, green, red, yellow and skin color. The color space regional decision and enhancement attenuation calculation modules corresponding to five regions calculate the enhancement region for each pixel, the enhancement amplitude and flat transition around the edge of the enhancement regions to reduce contouring effects. These are determined based on the region parameters stored in the color space regional parameter storage module. The color space component enhance module determines the adjustment amplitude of components in all directions based on the enhancement amplitudes calculated earlier. The regional adjustment module performs a part of the adjustment such as

compensating the luminance and limiting the data boundary, and then sends the adjusted data to RGB component adaptive regional enhancement module. This module computes each enhancement component of the pixel color depending on the color space region it is in, and adds the enhancement components with the corresponding original values and outputs the result.

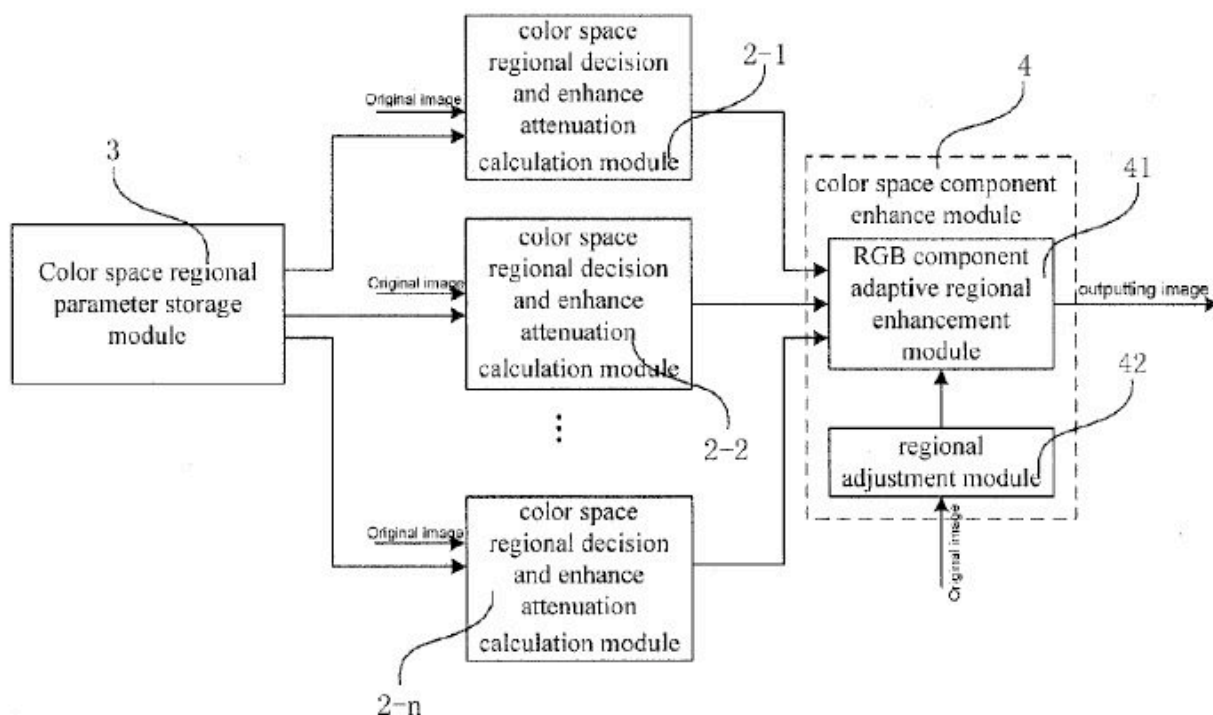


Fig. 4.10 Block diagram of the method discussed in Wang's pending patent

The above discussion on various existing and pending patents on color enhancement for images/video shows that the industry approach on color processing is largely ad hoc. While various smart implementations of color computation have been invented over the years, color processing is still performed in non-perceptual color spaces like RGB, LHS, YCC or YUV. Even though these spaces have their own computational advantages, none of them is a truly perceptual color space. Thus, an enhancement in a given region of such color space can produce a very

different result from that in another region within the same space. This happens because the relationships between the lightness, hue and chroma does not change in a linear fashion in such color spaces. To counter this problem, a color space is generally partitioned into several regions, and different enhancement strategies are employed for different regions. This often leads to contouring issues, which is solved by smoothening the enhancement in the transitional areas of various regions, as seen in case of some of the patented methods discussed in this section. Color processing in a non-perceptual color space has another important disadvantage. Luminance or saturation enhancement can frequently lead to a hue shift. Additional color correction modules are often implemented to resolve such issues.

The choice of color space is fundamentally important in digital color processing. A truly perceptual color space ensures the enhancement process is universal and more reliable, minimizing many artifacts and other issues commonly encountered in existing methods. Proposed algorithm, described in the next section, considers these aspects while employing methods that are image content independent and easy to implement since the processing is not ad hoc.

## 4.2 New Algorithm: Working Requirements

The main objective in color and contrast enhancement in video processing is to achieve the best possible combination of colorfulness and contrast enhancement in an efficient manner. Typically, the use of independent algorithms for color and contrast enhancement results in sub-optimal enhancement, and unwieldy combined tune-up. Following are the requirements of an image enhancement algorithm to be suitable for implementation in a video processing chain:

1. The algorithm must be automatic, i.e. deal with all content types without external intervention
2. It must integrate color and contrast enhancement functionalities
3. Enhancement must be adaptive to the overall image or video content
4. The overall lightness and saturation should be improved while maintaining the original hue
5. The achromatic colors must remain achromatic
6. Pixels with high saturation should be left unaltered to avoid any perceived loss in sharpness and undesirable color enhancement
7. The algorithm should not produce out-of-gamut colors or color artifacts (e.g. blotchiness)
8. The algorithm must be suitable for implementation in real time on the required target platform (software or hardware)

Temporal processing issues were not considered in this development.

### 4.3 Color Space

Following are the criteria for the suitability of a color space to be used in the implementation of a color enhancement algorithm:

1. Should be uniform in terms of perceived hue so that enhanced colors do not change in hues
2. Lightness prediction of chromatic colors must not have hue or lightness modulation dependency
3. Should be invertible functional mapping between XYZ (or some other fundamental color description) and the color space dimensions
4. Should be an opponent (has a neutral axis along one dimension) three-dimensional space
5. Transformation to and from a linear color space should not be computation expensive

Previous research showed that IPT color space satisfies all the above criteria [**Ebner 1998**].

The input image is assumed to be standard RGB (or sRGB). sRGB data are converted to CIEXYZ for the 1931 2° standard observer with an illuminant of D65. Eq. 4.1 shows the conversion from XYZ to IPT.

$$\begin{aligned}
 \begin{bmatrix} L \\ M \\ S \end{bmatrix} &= \begin{bmatrix} 0.4002 & 0.7075 & -0.0807 \\ -0.2280 & 1.1500 & 0.0612 \\ 0 & 0 & 0.9184 \end{bmatrix} \begin{bmatrix} X_{D65} \\ Y_{D65} \\ Z_{D65} \end{bmatrix} \\
 L' &= L^{0.43}; \quad L \geq 0 \\
 L' &= -(-L)^{0.43}; \quad L < 0 \\
 M' &= M^{0.43}; \quad M \geq 0 \\
 M' &= -(-M)^{0.43}; \quad M < 0 \\
 S' &= S^{0.43}; \quad S \geq 0 \\
 S' &= -(-S)^{0.43}; \quad S < 0 \\
 \begin{bmatrix} I \\ P \\ T \end{bmatrix} &= \begin{bmatrix} 0.400 & 0.4000 & 0.2000 \\ 4.4550 & -4.8510 & 0.3960 \\ 0.8056 & 0.3572 & -1.1628 \end{bmatrix} \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix}
 \end{aligned} \tag{4.1}$$

#### 4.4 Details of the Algorithm

The algorithm has three components, global lightness adjustment, local contrast enhancement and finally, saturation enhancement. Following sections describe these components. Details specific to the implementation have been excluded because of the proprietary nature of the work.

##### 4.4.1 Global Lightness Adjustment

In a typical image enhancement operation, increasing the saturation alone is not a good idea, as this can often lead to out-of-gamut or illegal colors. Increasing both saturation and intensity is even more likely to result in out-of-gamut colors. Out-of-gamut colors will necessitate clipping, which essentially leads to loss in contrast and details. Thus, in a typical image with normal exposure, the overall lightness needs to be reduced before increasing the saturation.

However, if an image is mostly dark to begin with, either due to under-saturation or due to high dynamic range of the image (which means a part of the image is quite bright at the same time),

the lightness may need to be increased before any perceived color enhancement can be attained. An example is shown in Figure 4.11. The horizon visible through the opening in the stone-wall is quite bright, while the other parts of the image are fairly dark. In this case, saturation enhancement needs to be higher than the normal to counteract the effect of a perceived loss of saturation due to an increase in the lightness. Thus, we must be able to determine whether an image needs to be darkened or lightened, and to what extent. This is achieved by the global lightness adjustment.



Fig. 4.11 “Cave”: an example image with a high dynamic range

Global lightness adjustment is done essentially through a Lookup Table (LUT). The curve is a straight line below lower threshold and above upper threshold. Thus pixel intensities less than the lower threshold and more than the upper threshold are not altered. These thresholds are parameterized, and can be used as user controls. Between these thresholds, the intensities are adjusted nonlinearly.

The intensity corresponding to a given Cumulative Distribution Function (CDF) is used to determine whether the image should be darkened or lightened. If this intensity lies below a pre-defined low CDF threshold, the image is lightened to the maximum level. If this intensity lies above a pre-defined high CDF threshold, the image is darkened to the maximum level. When the intensity lies in between, the amount of lightening or darkening is computed by linear interpolation.

Figure 4.12 shows the CDF of the “Cave” image shown in Figure 4.11 that needed the maximum amount of lightening. For this image, the intensity corresponding to a CDF of 0.5 is only 0.107, which means 50% of the image pixels have intensities below 0.107.

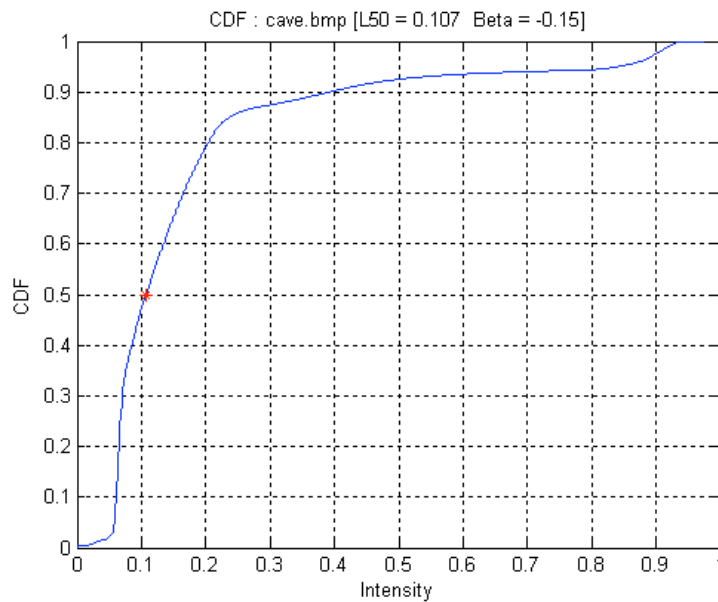


Fig. 4.12 Cumulative Distribution Function of the image “Cave”

Figure 4.13 shows an example image with normal dynamic range. Compared to the previous example, lightness variation in this image is more even. Figure 4.14 shows the CDF for this image. The intensity corresponding to a CDF of 0.5 is 0.56.



Fig. 4.13 “Faces”: an example image with normal dynamic range

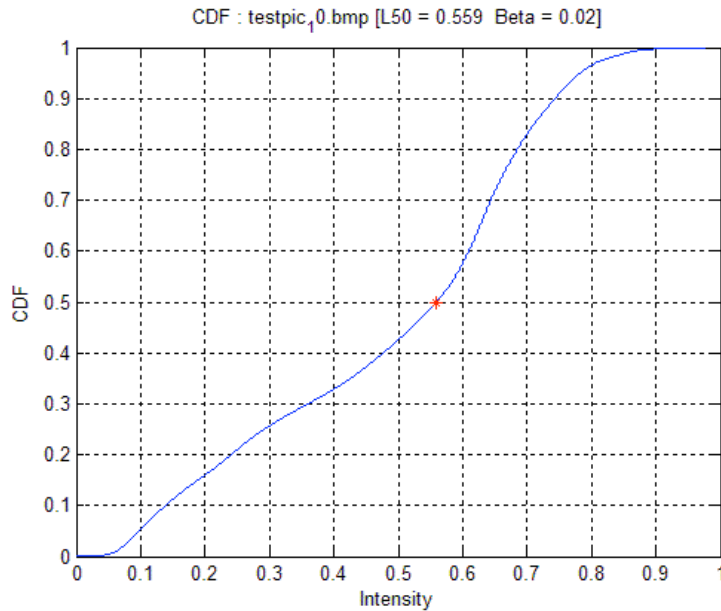


Fig. 4.14 Cumulative Distribution Function for the image “Faces”

An additional condition is imposed to ensure darkening or lightening does not cause some part of the image to be clipped. If a certain percent of pixel intensity in the CDF lies above a given value, it means a part of the image already has high intensity. In this case the image is not lightened. Similarly, if a certain percent of pixel intensity in the CDF lies below a given value, the image is not darkened.

#### **4.4.2 Local Contrast Enhancement**

A Low-Pass averaging filter is used to get a filtered version of the original intensity image. An exponent is applied to the difference of the original and the filtered intensity data while preserving the sign of the difference. The output intensity resulting from global lightness adjustment and local contrast enhancement is obtained from summing the two effects.

#### **4.4.3 Saturation Enhancement**

Similar to the global lightness adjustment, saturation enhancement is achieved through a Lookup Table. This avoids hard thresholds and the problems of artifacts associated with them. If the chroma of a pixel is below the low threshold, the color is likely to be achromatic and is left unaltered. Also, if the chroma of a pixel is above the high threshold, the color is already quite saturated and so is left unchanged. Colors in between these thresholds are increased in a nonlinear fashion.

If an image is significantly lightened, the perceived saturation reduces. Actual saturation enhancement in this case needs to be higher to counteract this effect. Whether an image is

significantly lightened was determined by a metric based on the CDF, and accordingly a higher saturation enhancement factor was used.

#### **4.5 Novelty of the proposed method**

Various published and patented methods reviewed in this chapter do not meet the objective of enhancing color and contrast in an effective and coordinated manner. The proposed algorithm addresses the need for a more complete color and contrast enhancement algorithm suitable for the video processing chain of consumer video systems. The new method is guided by the principles and foundations of color appearance and perception, and not by the statistical image processing. It takes advantage of a color space that is uniform in terms of perceived hue, thus ensuring the hue does not change during the processing, one of the main problems in color enhancement. A novel method for local contrast enhancement is also implemented in the algorithm.