Hindawi Publishing Corporation
EURASIP Journal on Image and Video Processing
Volume 2010, Article ID 175203, 19 pages
doi:10.1155/2010/175203

Research Article

Natural Enhancement of Color Image

Shaohua Chen and Azeddine Beghdadi

Laboratory L2TI, Institute of Galilee, University Paris XIII, France

Correspondence should be addressed to Shaohua Chen, shallowgrass@hotmail.com

Received 1 April 2010; Revised 5 July 2010; Accepted 6 July 2010

Academic Editor: Sebastiano Battiato

A new algorithm of Natural Enhancement of Color Image (NECI) is proposed. It is inspired by multiscale Retinex model. There are four steps to realize this enhancement. At first, the image appearance is rendered by content-dependent global mapping for light cast correction, and then a modified Retinex filter is applied to enhance the local contrast. Histogram rescaling is used afterwards for normalization purpose. At last, the texture details of image are enhanced by emphasizing the high-frequency components of image using multichannel decomposition of Cortex Transform. In the contrast enhancement step, luminance channel is firstly enhanced, and then a weighing map is calculated by collecting luminance enhancement information and applied to chrominance channel in color space CIELCh which enables a proportional enhancement of chrominance. It avoids the problem of unbalanced enhancement in classical RGB independent channel operation. In this work, it is believed that image enhancement should avoid dramatic modifications to image such as light condition changes, color temperature alteration, or additional artifacts introduced or amplified. Disregarding light conditions of the scene usually leads to unnaturally sharpened images or dramatic white balance changes. In the proposed method, the ambience of image (warm or cold color impression) is maintained after enhancement, and no additional light sources are added to the scene, and no halo effect and blocking effect are amplified due to overenhancement. It realizes a Natural Enhancement of Color Image. Different types of natural scene images have been tested and an encouraging performance is obtained for the proposed method.

1. Introduction

Image enhancement is one of the most important issues in image processing which can produce more suitable results than its original version for further image analysis and understanding. Many different approaches have been proposed in literature which can be roughly grouped into two categories: spatial domain methods and frequency domain methods. A thorough and comprehensive tutorial can be found in publications [1]. This paper, however, is mainly focusing on some recent methods based on Retinex theory [2] and its diversities that are applied to color image enhancement issue. Since the pioneering work of Land [3], wide applications of Retinex have been found in industrial and medical scenario and aerospace photography [4, 5]. Many algorithms have been proposed such as path version [6], iterative version [7, 8], and center/surround version [9].

However, image enhancement is not another application of detail retrieval or color constancy. These algorithms cannot be *directly* applied to this domain because most of them lead to several dramatic modifications such as light condition changes, color temperature alterations, and additional artifacts introduced or amplified. These techniques work efficiently indeed when serving as tools of extracting image details. However, disregarding light conditions of scene may result in unnaturally sharpened image appearance or dramatic white balance changes which are usually unwanted. Based on our previous work [10], we propose in this paper an algorithm of automatic Natural Enhancement of Color Image (NECI) method. There are four steps to realize this enhancement. At first, the image appearance is rendered by content-dependent global mapping for light cast correction, and then a modified Retinex filter is applied to enhance the local contrast. Histogram rescaling is used afterwards for normalization purpose. At last, the texture details of image are enhanced by emphasizing the high-frequency components of image using multi-channel decomposition of Cortex Transform [11]. In the contrast enhancement step,

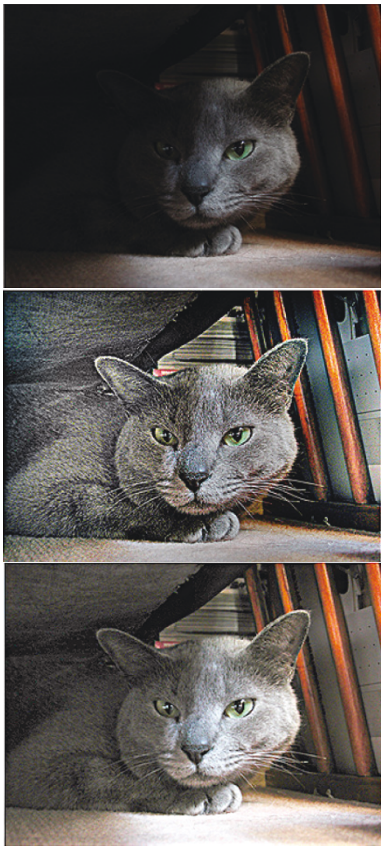


Figure 1: From top to bottom: original image, image enhanced by NASA Retinex [9], and by the proposed NECI method.

Figure 2: From top to bottom: original image, image enhanced by RGB 3-channel Retinex [7], and by the proposed NECI method.

luminance channel is firstly enhancement, and then a weighing map is calculated by collecting luminance enhancement information and applied to chrominance channel in color space CIELCh which enables a proportional enhancement of chrominance compared with the luminance. It avoids the problem of unbalanced enhancement in classical RGB independent channel operation.

In this work, it is believed that image enhancement should be different from detail retrieval or color constancy which often leads to several dramatic modifications to image such as light condition changes, color temperature alteration, or additional artifacts introduced or amplified. Disregarding light conditions of scene usually leads to unnaturally sharpened images or dramatic white balance changes which are usually unwanted. In the proposed method, the ambience of image (warm or cold color impression) is maintained after enhancement, and no additional light sources are added to the scene, and no halo effect and blocking effect are amplified due to over-enhancement which leads to a Natural Enhancement of Color Image.

The structure of this paper is organized into 6 sections including the current Section 1 of introduction. A problem statement will be given at first to show the insufficiency of natural enhancement of color image by some state-of-the-art methods. Section 3 describes the flowchart of the proposed NECI method with brief explanations and some typical results. Details of theoretical analysis and practical implementations will be presented in Section 4. Different types of natural scene images are shown in Section 5 followed by conclusion and perspective works in Section 6.

2. Problem Statement

As stated in introduction, a natural enhancement algorithm should avoid dramatic alternation of lighting conditions to the scene, and not introduce additional artifacts or amplifying hidden distortions of images. Enhancement without considering the relative relationship between bright and dark zones will result in additional light sources introduced to image. Figure 1 shows a hiding cat coming to be fully exposed to light after image enhancement. It seems to have another light source projecting to the cat which is *not* true. Such an alteration of light source leads to a confusing comprehension of the scene.

Color temperature change is another artifact of some image enhancement techniques. Figure 2 shows a picture of sunset. However, a color constancy algorithm often results in a bluish sky due to unbalanced three-channel operation. This change of color temperature will certainly change the design of the photographer who wants to record the warm ambience of sunset.

Last but not least, most image enhancement algorithms work with noncompressed image or perceptually lossless compression version. However, in practice many images have

(a) (b) (c)

Figure 3: (a) Original image; (b) image enhanced by luminance histogram equalization; (c) image enhanced by NECI.

already been compressed with loss such as the photos or videos in Internet. Over-enhancement to these data often results in either visible halo effect or amplified blocking effect and ringing effect. For instance, the middle image in Figure 3 shows many blocking-effects which were hidden due to dark luminance before enhancement. Therefore, cautions must be taken in these sensible regions to avoid over-enhancement. Otherwise, annoying artifacts may be resulted. The proposed NECI intends to be conservative in these artifact-sensitive regions for heavily compressed image and avoids over-enhancement by not exaggerating the enhancement weighting coefficients.

3. Flowchart of NECI

The proposed method is separated into four steps: at first, the image appearance is rendered by content-dependent global mapping for light cast correction, and then a modified Retinex filter is applied to enhance the local contrast. Histogram rescaling is used afterwards for normalization purpose. At last, the texture details of image are enhanced by emphasizing the high-frequency components of image using multi-channel decomposition of Cortex Transform. Figure 4 shows the global flowchart.

In the first step of global mapping, gamma correction is often applied using logarithm curve. However, for many compression algorithms, the dark-zones of image are often heavily compressed by coding system and therefore more sensible to over-enhancement. Logarithm curve amplifies the small intensities of dark zone pixels which makes blocking effect or ringing effect more visible after enhancement. For low-intensity pixels, we designed a circular curve to replace gamma correction tone mapping in the proposed work which gives moderate gain in dark zone so that the hidden artifacts remain tolerable after enhancement. This step will be discussed in detail in Section 4.1.

Step two includes a luminance enhancement using modified Retinex and chrominance enhancement using enhancement map and histogram rescaling in color space CIELCh. Detailed discussion can be found in Section 4.2.

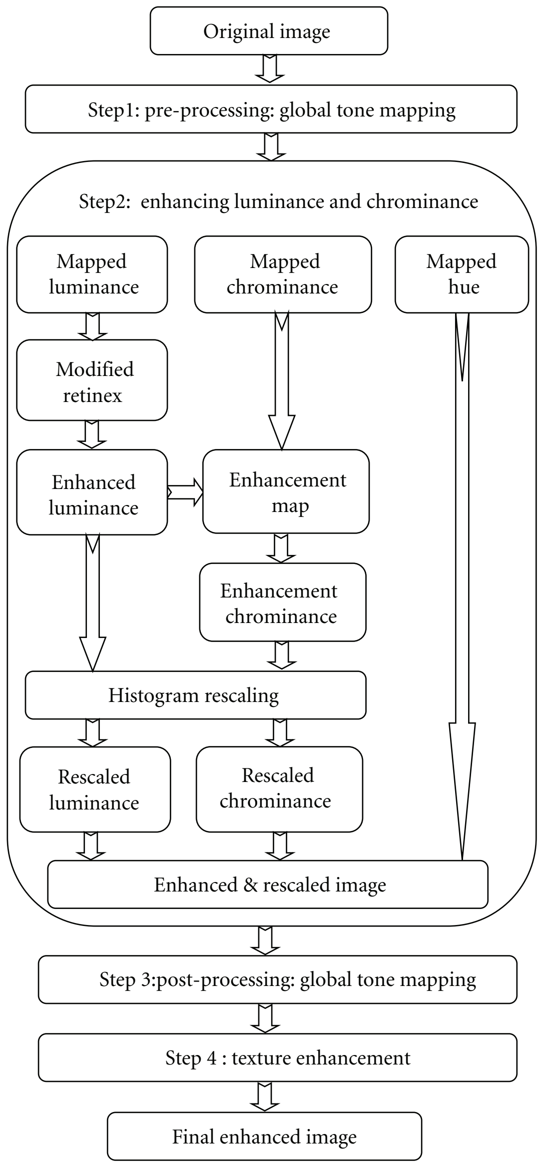
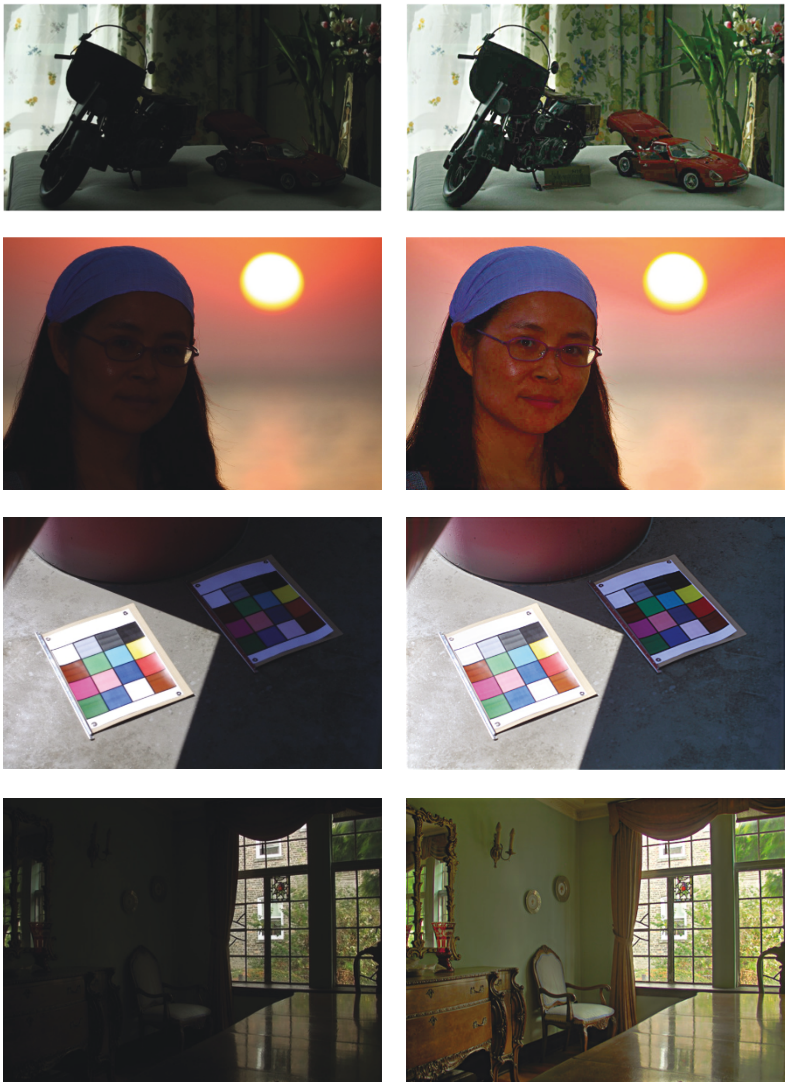


Figure 4: Global flowchart of NECI.



(a) (b)

Figure 5: (a) original images, (b) NCEI results.

The proposed NECI method is inspired by a computational model of multi-scale Retinex [12, 13], while an additional logarithm function is applied to mask image (estimation of background using Retinex filter) for local contrast calculation to avoid introducing halo effect or amplifying blocking or ringing effect of the compressed image. For chrominance enhancement, applying Retinex independently to three color channels (RGB) usually results in false colors and hue-shift. In the proposed work, only luminance channel is used for a local contrast calculation, and the enhancement information is used as reference map applying to chrominance channel in color space CIELCh so that a balanced enhancement of chromatic components can be achieved. A histogram rescaling operation is followed for black and white point correction at the end of contrast enhancement, and only 99% of histogram is used to remove the influence of a few pixels with extreme intensities. The chrominance enhancement and histogram rescaling will be also discussed in Section 4.2.

The enhanced image after histogram rescaling will be reconstructed from CIELCh to RGB space. The resulted image, although with contrast enhanced, may still need global mapping for a normal tone appearance. Therefore, another global mapping step using the same principle as step one is applied in step 3 as posttreatment to ensure the global appearance of the enhanced image.

Finally, the texture information will be enhanced using multi-channel decomposition of Cortex Transform. The advantage of Cortex Transform over other approaches (such as sharpening the contour with Laplacian filter) is that the multi-channel decomposition can better capture the texture information in *several* different spatial frequency bands whereas the Laplacian-like approach usually captures *one* subband frequency which usually cannot achieve *gradually*

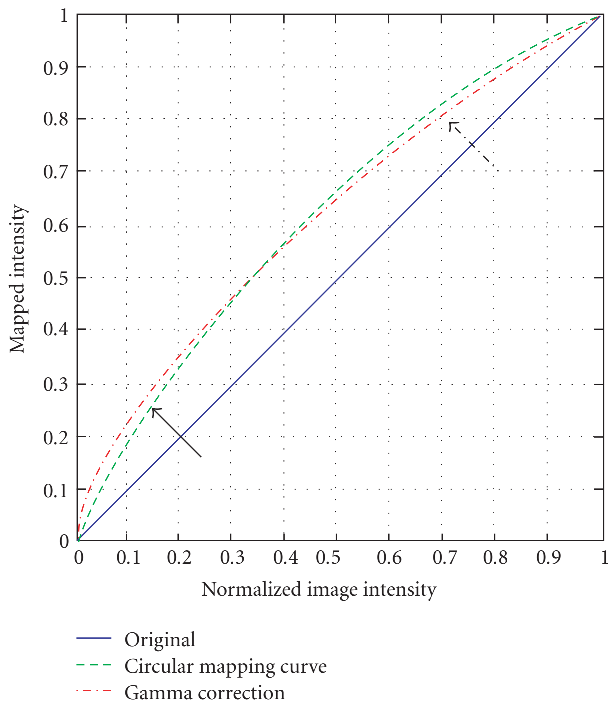


Figure 6: Global mapping curve using modified gamma correction.

sharpened contour. The texture enhancement using Cortex Transform will be discussed in Section 4.3.

Figure 5 shows some test results. As can be seen that no additional confusing light sources are introduced into scene after enhancement, and both luminance and chrominance contrast are increased without causing halo effect or overamplifying blocking effect and ringing effect. In the proposed NECI method, there are no parameters to be trained or modified for different image contents which is nevertheless crucial to some algorithms [7, 14]. The computational cost is increased by Cortex Transform so that the NECI method can only be used as off-line method due to its time of computation.

4. Analysis and Implementation Details

In this section, all of the four steps of NECI will be discussed in details with intermediate results to show the improvement of image contrast by each step.

4.1. Global Tone Mapping Using Modified Gamma Correction. In the proposed work, a modified gamma correction is used. For low-intensity pixels, the mapping curve is an arc of circle instead of a logarithm function as shown in Figure 6. It can be seen that an arc gives a relatively moderate gain in dark zone (referred by straight-line arrow) which avoids over-enhancement of the hidden artifacts (usually blocking and ringing effect from compression). However, for high intensity of pixels (referred by dashed-line arrow), the gamma correction curve is used since these regions correspond to bright zone of image and increasing the luminance of these zones risks of saturating the luminance and consequently losing contrast information.

4.1.1. Image Key Value and Adaptive Global Mapping. In order to be adaptive to different image contents, the gamma value and the radius of mapping circle are designed to be functions of image key value which can be regarded as an index of dominating tone of image. Figure 7 shows some image examples with their corresponding histograms. As can be seen, the low-key image corresponds to the dark images, and high-key image corresponds to brighter one.

The key value of image can be calculated using

$$\text{key} = e^{\sum_x \sum_y [\log(L(x,y))+\varepsilon]/\text{size}(I)}, \tag{1}$$

where $L(x, y)$ is the luminance of pixel (x, y) of image I and ε is added to avoid problem of logarithm of zero. Figure 8 shows the relationship of key value and the dominant tone of image. In color space CIELCh, the luminance value varies from 0 to 100. Figure 8(a) is a noisy synthetic image whose dominant luminance is around 50, and the resulted key value using (1) is 49.5210. Equation (1) is less sensitive to a few extreme intensities in image compared with a simple mean value of luminance thanks to the sum of logarithm operation. In our work, the image key value from 50 to 60 is categorized as a normal tone image, and the preprocessing of global mapping whose purpose is light cast correction can be omitted for this group of images.

4.1.2. Adaptive Global Mapping for Low Intensities. For low-intensity pixels, the mapping curve is an arc of circle as discussed above to avoid over-enhancement, and the empirical function between radius of circle and key value is given by (2).

$$r = \begin{cases} 3 \times \log\left(\dfrac{\text{key}}{10} + \varepsilon\right) & \text{for key} \le 50, \\ 3 \times \log\left(10 - \dfrac{\text{key}}{10} + \varepsilon\right) & \text{for key} \ge 60, \end{cases} \tag{2}$$

where r is the radius of circle and ε is a small positive constant to avoid the problem of logarithm of zero. The mapping operation is applied by

$$I_{\text{gm}} = \begin{cases} y_0 + \sqrt{r^2 - \left(I_{\text{orig}} - x_0\right)^2} & \text{for key} \le 50, \\ y_0 - \sqrt{r^2 - \left(I_{\text{orig}} - x_0\right)^2} & \text{for key} \ge 60, \\ I_{\text{orig}} & \text{otherwise}, \end{cases} \tag{3}$$

where I_{orig} is original image, I_{gm} is the globally mapped image, and (x_0, y_0) is the coordinate of the mapping circle center. It can be seen from (3) and Figure 6 that if image key value is smaller than 50, the arc of circle will cave in *upwards* compared to straight line (which is the no-mapping case) to amplify tone values of dark image. However, if the key value is larger than 60, the arc will cave in *downwards* compared to straight line to compress the brightness of image. For image with key value between 50 and 60, no global mapping

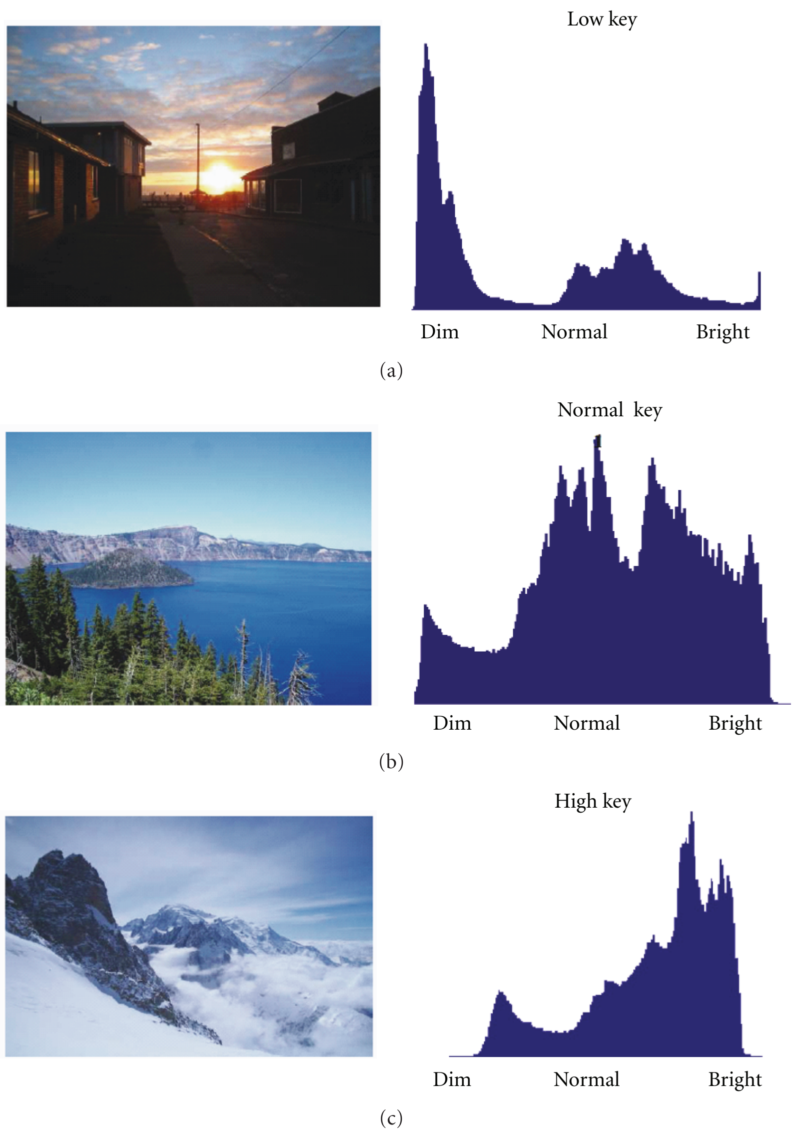


FIGURE 7: Image dominating tone and key value [12].

is needed since the original picture has a normal dominant tone.

The value of r is capped to 1.4 in our work because although r equals to 1 may be the smallest available radius for mapping curve as shown in Figure 9, such a large curvature of mapping circle will result in over-enhancement of dark zone such as in the case of gamma correction.

4.1.3. Adaptive Global Mapping for High Intensities of Underexposed Scene. For underexposed image scene (key value smaller than 50), the global mapping for high-intensity pixels appears relatively more bright due to the presence of the dark regions (simultaneous contrast phenomenon). To preserve better the contrast information in this bright zone, the logarithm curve will be applied instead of circular curve because the logarithm now gives more moderate gain than circular curve. That is, for underexposed scene, the low-intensity pixels will be globally mapping using circular curve, whereas the how-intensity pixels will be mapped using logarithm curve as shown in Figure 7. To smooth the intersection of the two curves, the gamma value is calculated by

$$(x_1 - x_0)^2 + (y_1 - y_0)^2 = r^2, \quad y_1 = x_1{}^{\gamma}, \tag{4}$$

where (x_1, y_1) is the point of intersection of circular curve and logarithm curve, y_1 is empirically calibrated to be 15% of the mapped intensity (vertical axis), and (x_0, y_0) and r are the origin and radius of the mapping circle. The value of γ can be calculated using these two equations since it is the only unknown variable. The mapped intensity can hence be calculated using

$$I_{gm} = I_{orig}{}^{\gamma}, \tag{5}$$

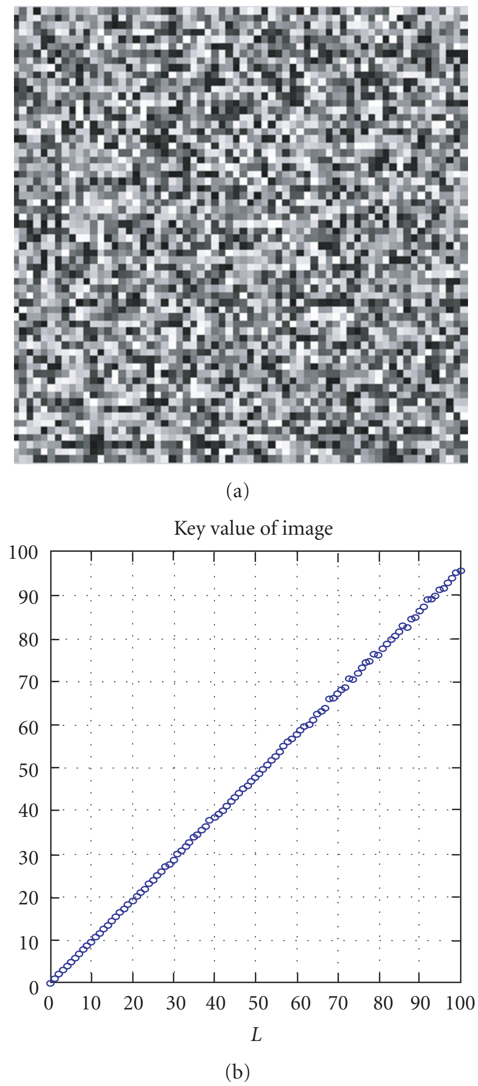


Figure 8: (a) Test sample with dominant tone around 50. (b) Relationship between dominant tone and key value. Horizontal axis is dominant tone of noisy images (varying from 0 to 100) and vertical axis is the corresponding key values varying from 0 to 100.

where I_{orig} and I_{gm} refer to the original image and its globally mapped version, respectively.

For overexposed image, traditional luminance component of color space usually loses some information due the almost saturated brightness for this type of images. However, if the Principle Component Analysis (PCA) is applied to color image, then its primary vector contains usually more information than that of classical luminance channel since this PCA vector concentrates most of image information from all of three channels. By this means, the details in bright zone of overexposed image can be better extracted with PCA first vector than traditional luminance representation for further contrast enhancement procedures.

This step of global mapping serves as preprocessing in NECI, and the same process will be reapplied to the enhanced image after step 3 as a posttreatment to ensure the light cast of the enhanced version after Retinex contrast enhancement,

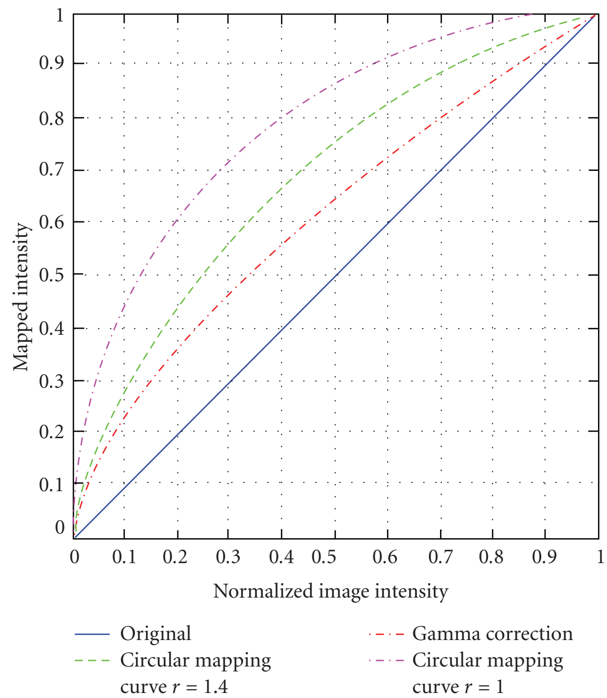


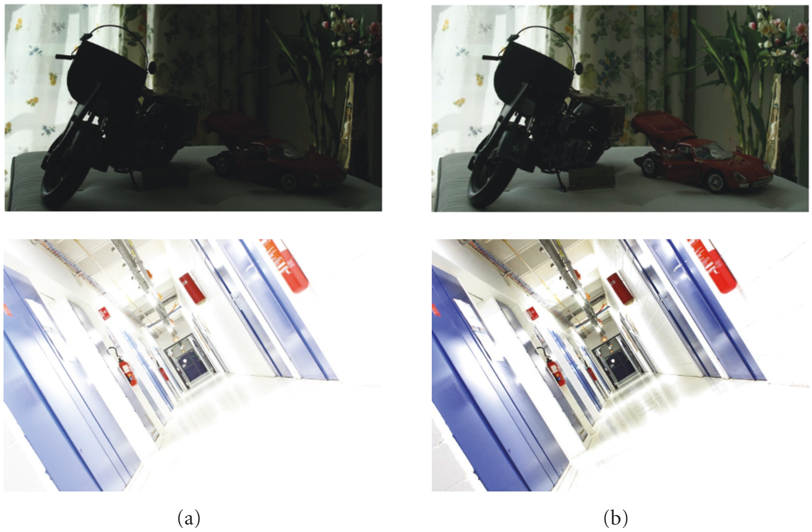
Figure 9: The comparison between mapping curves. The magenta dashed line corresponds to circular mapping curve $r = 1$.

histogram rescaling. Figure 10 gives some examples of the output of global mapping. As can be seen that the adaptive global mapping renders image from extreme illumination conditions (top image: underexposed photo; bottom image: overexposed photo) to nearly normal condition. Now the inputting image is ready for luminance, and chrominance enhancement which will be discussed in next section.

4.2. Luminance and Chrominance Enhancement. This step performs luminance and chrominance enhancement in two stages. First of all, the original RGB image is transferred to color space CIELCh to separate luminance, chrominance and hue components. The contrast information in luminance channel is enhanced using a modified multi-scale Retinex. The enhancement information is used in an enhancement map to weight the chromatic component. By this means, the luminance and chrominance will be enhanced proportionally to avoid unbalanced enhancement such as RGB independent channel operation.

Secondly, histogram rescaling is applied to both enhanced luminance and chrominance channel to realize normalization of the results. This statistical rescaling for black and white point correction removes the influences of some extreme intensity of pixels. The hue component in CIELCh remains unchanged to maintain the hue constancy property, and the image is reconstructed with enhanced luminance and chrominance together with the unchanged hue component from CIELCh space to RGB space.

4.2.1. Luminance Enhancement Using Modified One-Filter Retinex. This step is inspired by a computational model of



(a) (b)

Figure 10: (a) Original image; (b) adaptive global mapping results.

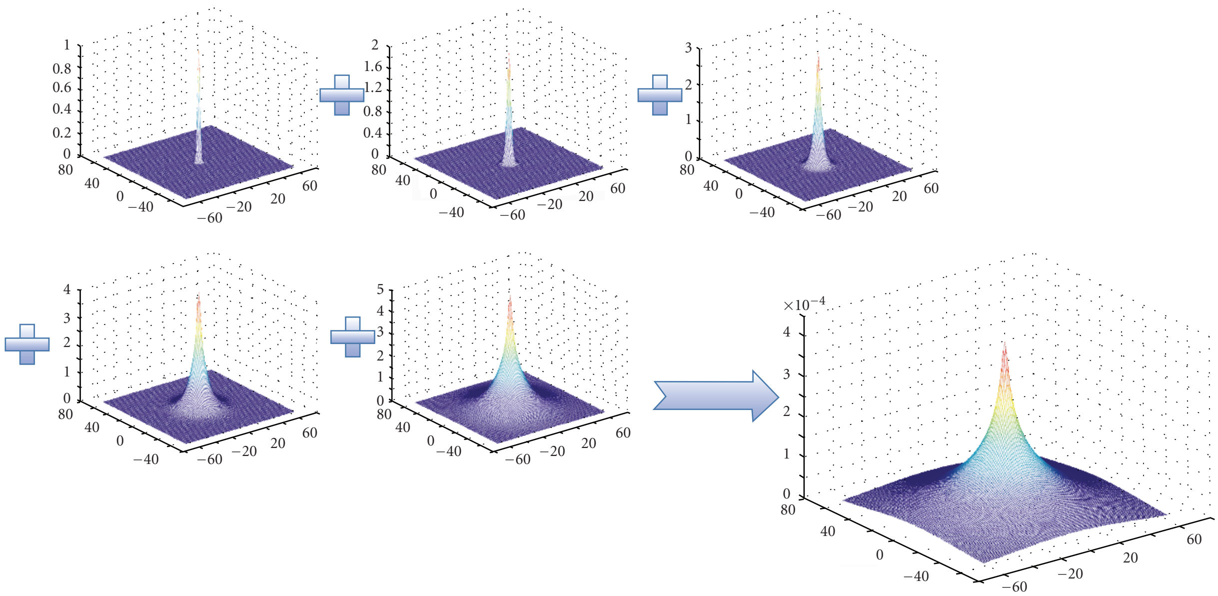


Figure 11: Sum of a group of Gaussian to form a Retinex filter for local background calculation.

multi-scale Retinex [13]. An additional logarithm function is applied to image mask before taking ratio between the mapped luminance and the mask image to avoid halo effect. The reason for the application of logarithm will be demonstrated in a later part of this section. The principle of one-filter Retinex is at first recalled below for a self-complete introduction.

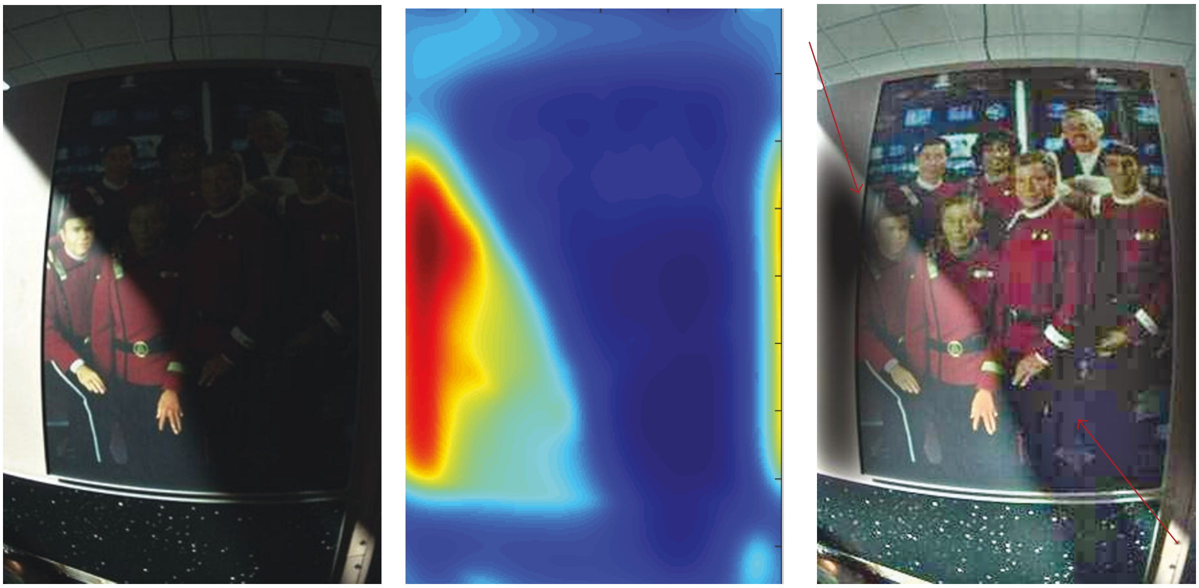
To extract contrast values, we usually use the center intensity divided by its local background. But actually the perception of contrast will be influenced by not only immediate neighbors but also by the contrast value of distant pixels [2, 3], and many different versions of Retinex have been proposed to describe this phenomenon including path version, central/around version, and multi-scale version. The computational model of multi-scale Retinex [13] uses the following equations to construct a filter for local background estimation of each pixel:

$$L_{\text{mask}} = L_{\text{input}} * F_r, \tag{6}$$

$$F_r = \sum_{i=1}^{\lfloor \log 2(K) \rfloor} e^{-(x^2+y^2)/2^{2i}}, \tag{7}$$

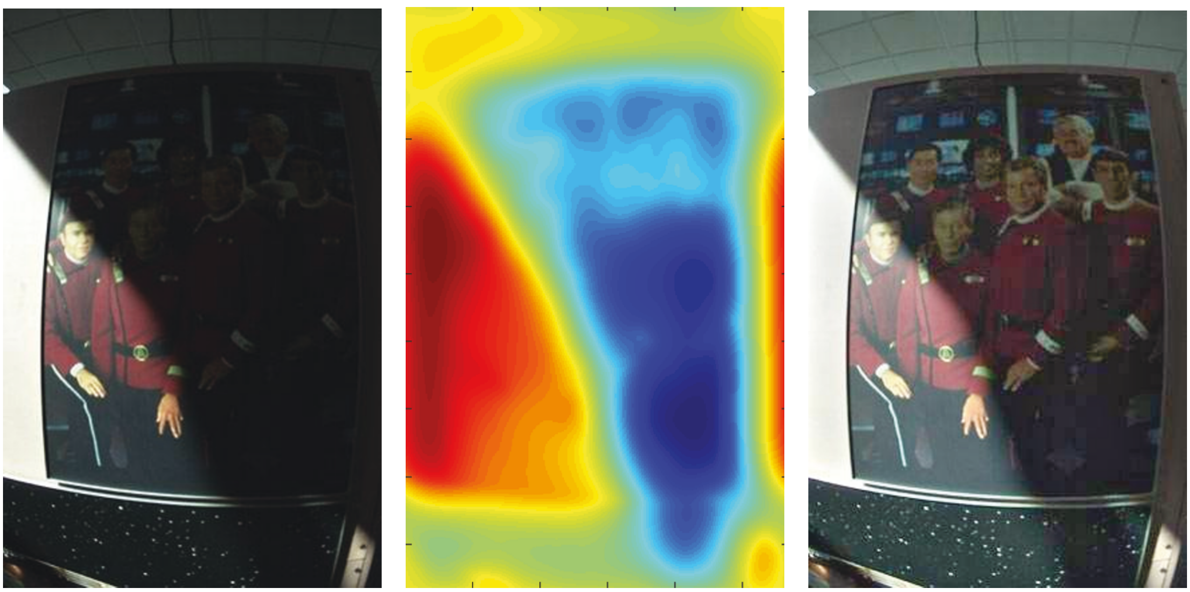
$$K = \frac{\max\left(\text{size}\left(L_{\text{input}}\right)\right)}{8}, \tag{8}$$

where (x, y) is the coordinate of the image pixel varying from 1 to K, F_r is the mask window, L_{input} is the input image, and



(a) (b) (c)

Figure 12: (a) Original image; (b) pseudocolored mask image (red signifies brighter zone, and blue signifies darker zone); (c) obtained final NECI image with halo effect in dark area and halo effect in bright area due to over-enhancement.



(a) (b) (c)

Figure 13: (a) Original image; (b) logarithm of mask image; (c) obtained final NECI image with less halo and blocking effect.

L_{mask} is the mask image (the estimation of local background) obtained by a convolution between L_{input} and F_r. Figure 11 shows profiles of each sub-Gaussian form and the resulted filter (which is sum of all the sub-Gaussian).

From (7) and (8), we can see that the number of Gaussian and its variance is proportional to image size, and the resulted filter F_r has a pointed shape and a large base. If we make convolution using this filter with the original image as referred in (6), pixels not only from immediate neighbors but also from distance will make contribution to the background calculation, and their contributions are weighted by their distances from the center using Gaussian curves. This background compared with local background such as a 5×5 block corresponds better to our perception of contrast.

Having obtained the mask image, the Retinex image can be calculated by the ratio of input luminance and image mask. However, in the proposed NECI method, an additional

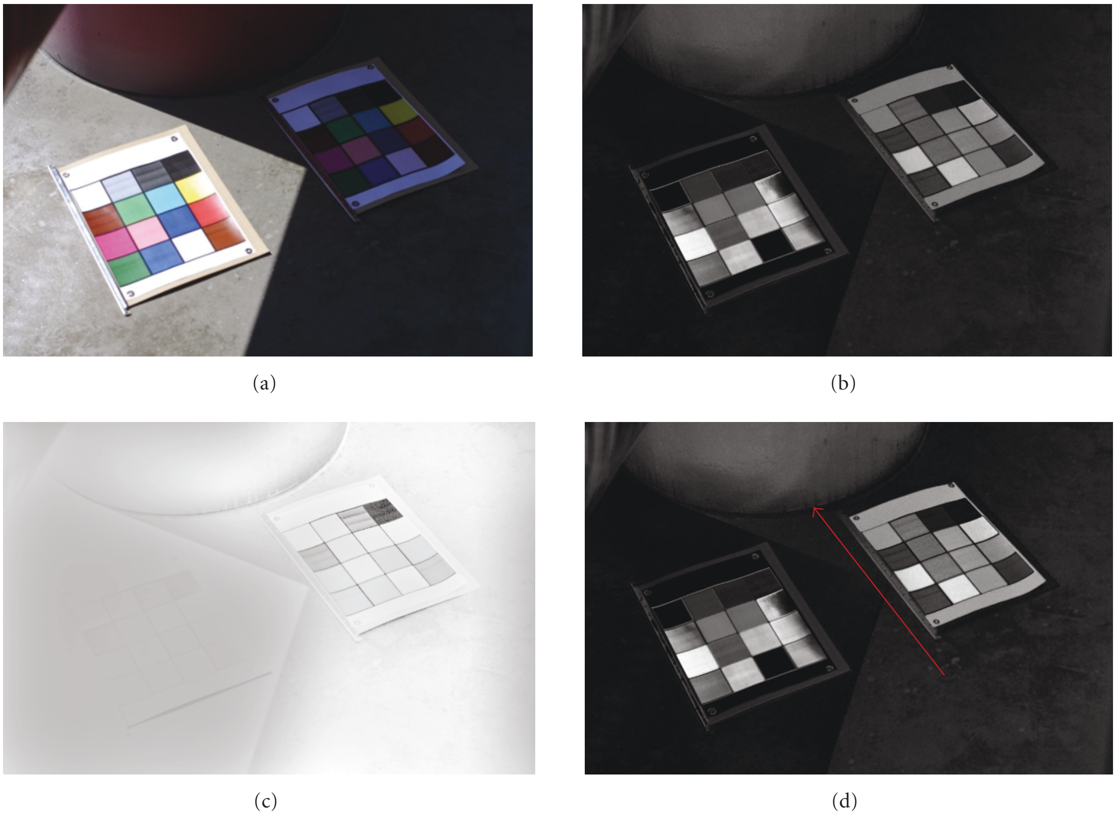


Figure 14: (a) Original image, (b) chrominance channel after global mapping, (c) normalized reference map using luminance enhancement information, and (d) enhanced chrominance channel.

logarithm function is applied to image mask before taking the ratio as

$$L_{\text{retinex}} = \frac{L_{\text{gm}}}{\log_{10}(L_{\text{mask}+\varepsilon}) + \varepsilon}, \tag{9}$$

where L_{mask} is the image luminance mask (estimation of local background), L_{retinex} refers to then enhanced luminance (Retinex output), and L_{gm} refers to globally mapped luminance of step 1. The small positive constant ε is added to avoid problem of logarithm of zeros and division of zero.

For the contrast value, if we use directly the intensity of central pixel divided by its background obtained from Retinex filter, it may lead to over-enhancement problem. For the dark regions, the value of ratio can be very high because the denominator is the intensity of dark regions which is very small. And if the image is heavily compressed by JPEG, for instance, the blocking effects in dark zone will become more visible because of the high values resulted from the division operation of (9). On the other hand, for brighter zone, since the background intensity is high, then the ratio between the central to its background will be relatively small which leads to some gray area in bright zone (which is the halo effect). Figure 12 shows this problem. The blocking effects and halo effect is referred by arrows.

In our work, a logarithm function is applied to the mask image so that the dynamic range of the background is compressed. The dark area is therefore enlightened after normalization, and the bright area is compressed on the other hand. The new ratio between the central pixels to the mask image can therefore avoid over-enhancement. Figure 13 gives the corresponding results with the logarithm function applied to image mask.

4.2.2. Chrominance Enhancement Using Reference Map. The enhancement information of luminance channel is used as a reference map to weight the chromatic component to ensure a proportional improvement between these two channels. The application of CIELCh enables direct access to chrominance channel compared with RGB and CIELab color spaces. The following equations show how to obtain the enhanced chrominance:

$$M_{\text{ref}} = \frac{L_{\text{enh}}}{L_{\text{gm}} + \varepsilon}, \tag{10}$$

$$C_{\text{enh}} = C_{\text{gm}} \times M_{\text{ref}}, \tag{11}$$

where M_{ref} refers to the reference map. ε is a small positive constant to avoid the problem of division of zero. L_{enh} and C_{enh} refer to the enhanced luminance and chrominance, and L_{gm} and C_{gm} refer to the luminance and chrominance after step 1 of global mapping. Figure 14 gives an example of reference map and the enhanced chromatic component. The local chromatic contrast has also been increased as indicated by arrow in figure.

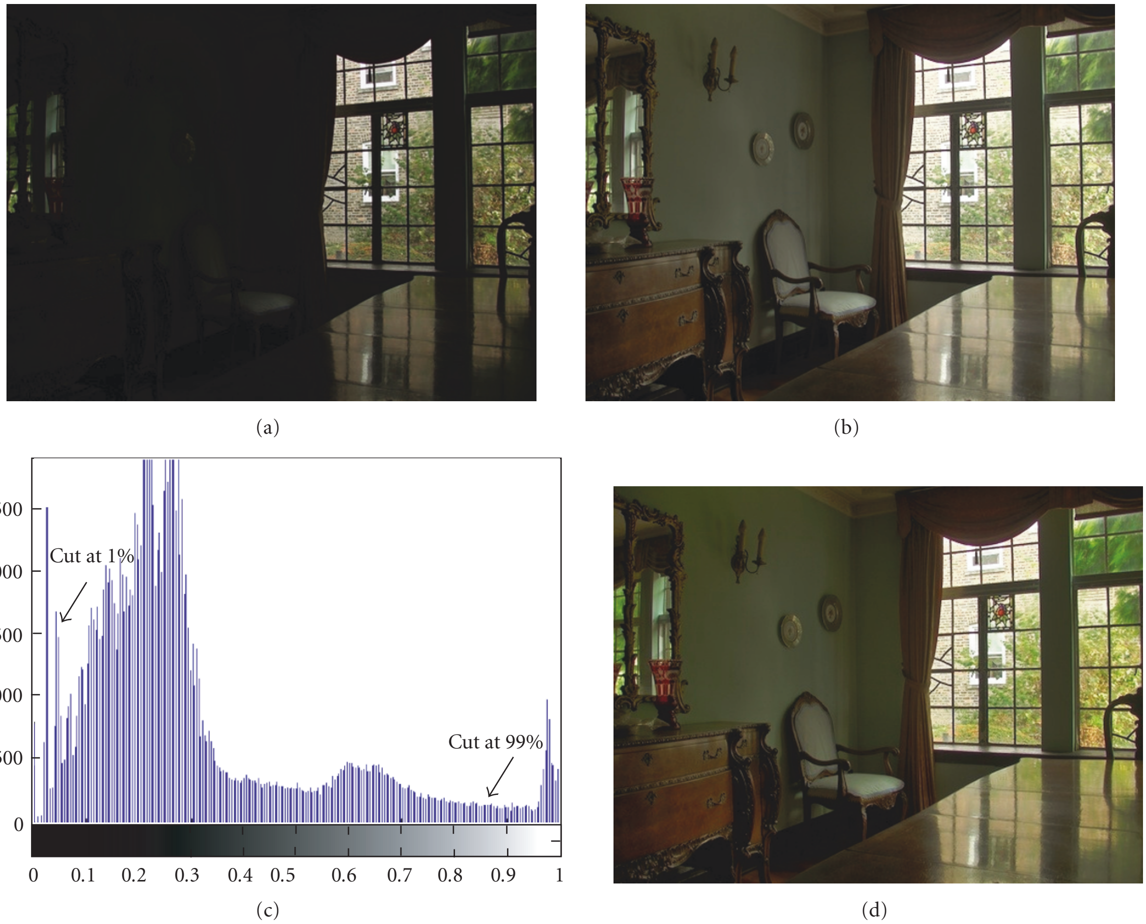


Figure 15: (a) Original image, (b) enhanced image after luminance and chrominance enhancement, (c) histogram rescaling principle, and (d) histogram rescaled version of the enhanced image.

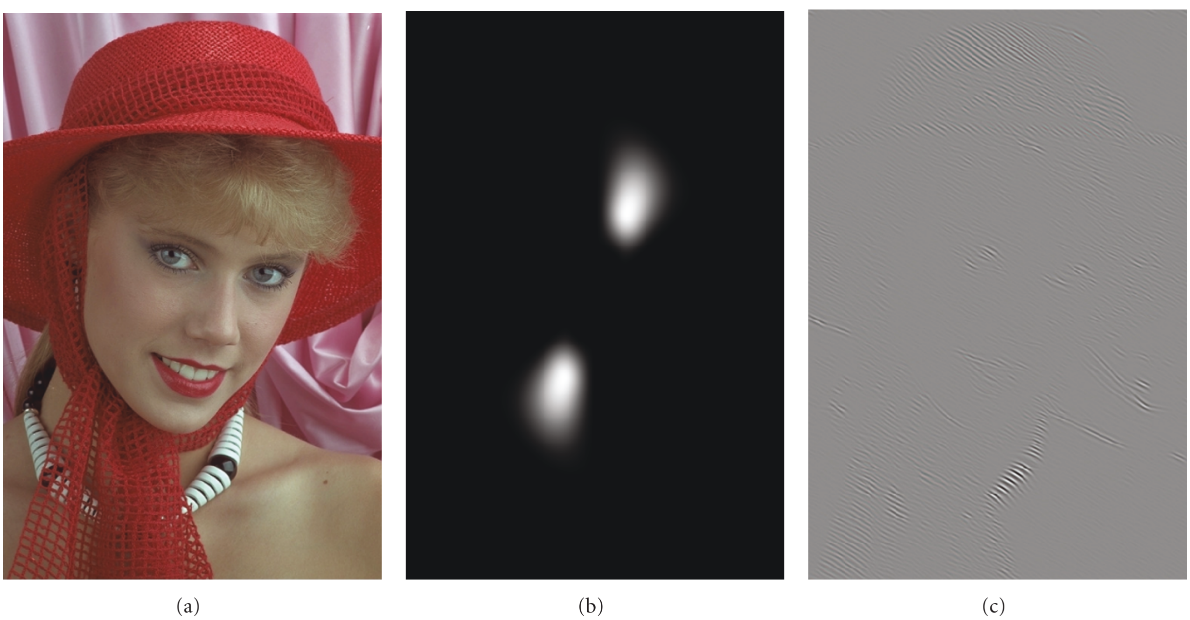


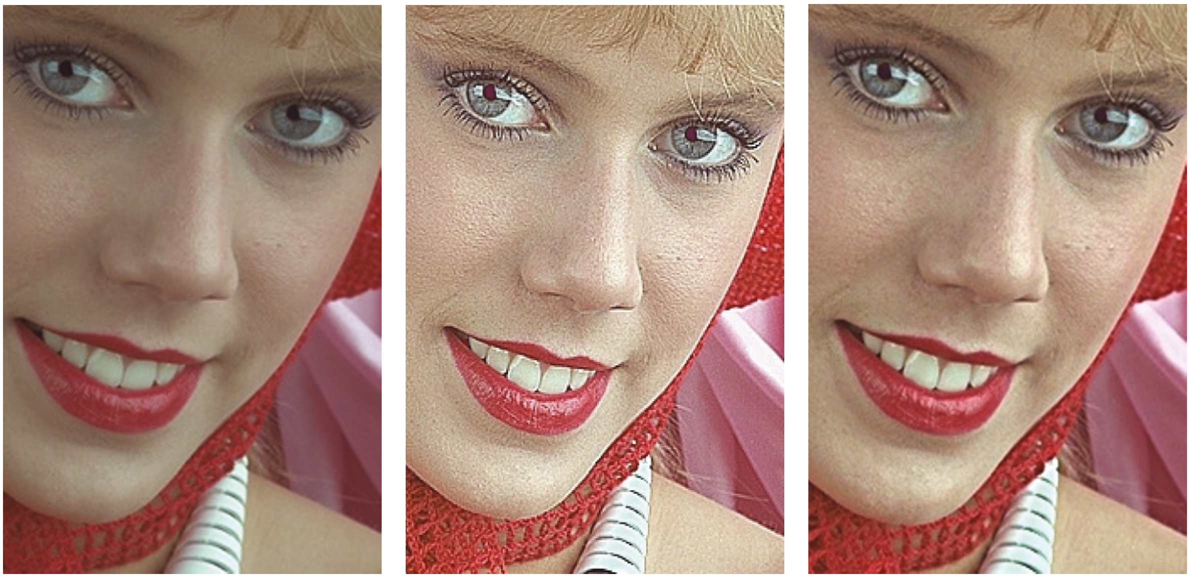
Figure 16: (a) Original image. (b) One subband of Cortex Transform profile. (c) Texture information extracted using this subband filter.

Figure 17: (a) Original image. (b) Texture details extracted using Cortex Transform. (c) Enhancement output of step 3. (d) Final result of NECI by strengthening the texture information of step 3 output.

4.2.3. Histogram Rescaling for White Point Correction. The enhancement of luminance and chrominance may sometimes result in unpredictable extreme bright points due to the division operators in (9) and (10). In this case, a white point correction is necessary before linear normalization since the maximum value of the obtained result does not represent significantly the image content [12]. A group of bright pixels must be used in white point estimation instead of one single-valued maximum, which turns out to be a histogram-based rescaling. In the proposed method, the histogram of enhanced image is cut from 1% to 99% of the whole range. This statistical normalization avoids the influence of a few extreme dark or bright pixels due to over-enhancement. Figure 15 shows an example of rescaled image after black and white point correction. As can be seen from this figure, histogram rescaling prevents color from washing-out and a more saturated image can be obtained.

Concerning the hue component, since generally a hue-constant enhancement is preferred for coherent rendering of original image, the hue component after global mapping remains unchanged during enhancement. After reconstruction of the enhanced image from CIELCh to RGB space, post-treatment using similar global mapping as step 1 is applied to ensure the global appearance of the enhanced image.

4.3. Texture Enhancement Using Multi-Channel Decomposition of Cortex Transform. Cortex Transform is a multi-channel representation using radial as spatial frequency



(a) (b) (c)

Figure 18: (a) Original image; (b) local contrast enhanced with contour sharpened by Laplacian filter; (c) local contrast enhanced with detail enhanced by Cortex Transform.

channel and divides the radial into sections each of which represents different orientations. This multi-channel model is similar to Laplacian pyramid, and composed by two types of filters: the radial filter named Dom Filter and the orientation filter named Fan filter. The Dom filter corresponds to selectivity on spatial frequency and Fan filter corresponds to selectivity on orientations. A low-pass two-dimensional filter called Mesa function will be used to generate the Dom filter. We do not recall the complicated deduction of formulas sets for the clarity of presentation. The whole set of formulas of Cortex Transform can be found in [11]. A classical Cortex Transform decomposes image into 31 subimages, including 5 different spatial frequency bands each of which is divided into 6 subimages corresponding to one orientation of its spatial frequency, plus 1 extra base image corresponding to low-frequency component of original image. By implementing Cortex Transform filters, only those image components under certain spatial frequency and certain direction are extracted. Figure 16 shows an example of one subband Cortex Transform filter profile in frequency domain and the texture information extracted from image using this subband filter.

In this work, the texture information of the enhanced image is strengthened by emphasizing the high-frequency components of image using

$$I_{\text{final}} = I_{\text{enh}} + \alpha \sum_{k=3}^{5} (I_{\text{enh}} * \text{Dom}_k), \tag{12}$$

where the I_{final} is the final result of NECI, I_{enh} is the enhancement output of step 3, and Dom_k is the kth Dom filter of Cortex Transform in spatial domain. The operator $*$ signifies convolution between the original image and the Cortex Transform filter subband profile. Coefficient α is used to adjust texture enhancement forces. It is set to be 0.33 in our work. Using (12), the highest three spatial frequency components (which correspond to image details) will be strengthened so that the texture information will be more evident than its original version. Figure 17 shows an example of texture enhancement using Cortex Transform.

The advantage of Cortex Transform over Laplacian filter approach to enhance contour sharpness is that the former is multi-channel decomposition and therefore can better capture the texture information in *several* different spatial frequency bands whereas the latter usually captures only one subband in frequency domain. As a result, using Cortex Transform high-frequency component to enhance image, more texture details information can be strengthened while unpleasant oversharpened contour (caused by over-enhancement of one single frequency band) can be consequently avoided. Figure 18 gives an example of comparison.

4.4. Implementation Details of NECI. By integrating all the discussions above, a comprehensive flowchart with detailed implementation instructions is given in Figure 19. The proposed NECI implementation can be briefly summarized into four steps.

(i) Pretreatment using modified gamut mapping which is adaptive to image dominating tone;

(ii) Image enhancement including.

  (a) luminance enhancement using modified one-filter Retinex,

  (b) chrominance enhancement using reference map,

  (c) histogram rescaling for enhanced luminance and chrominance,

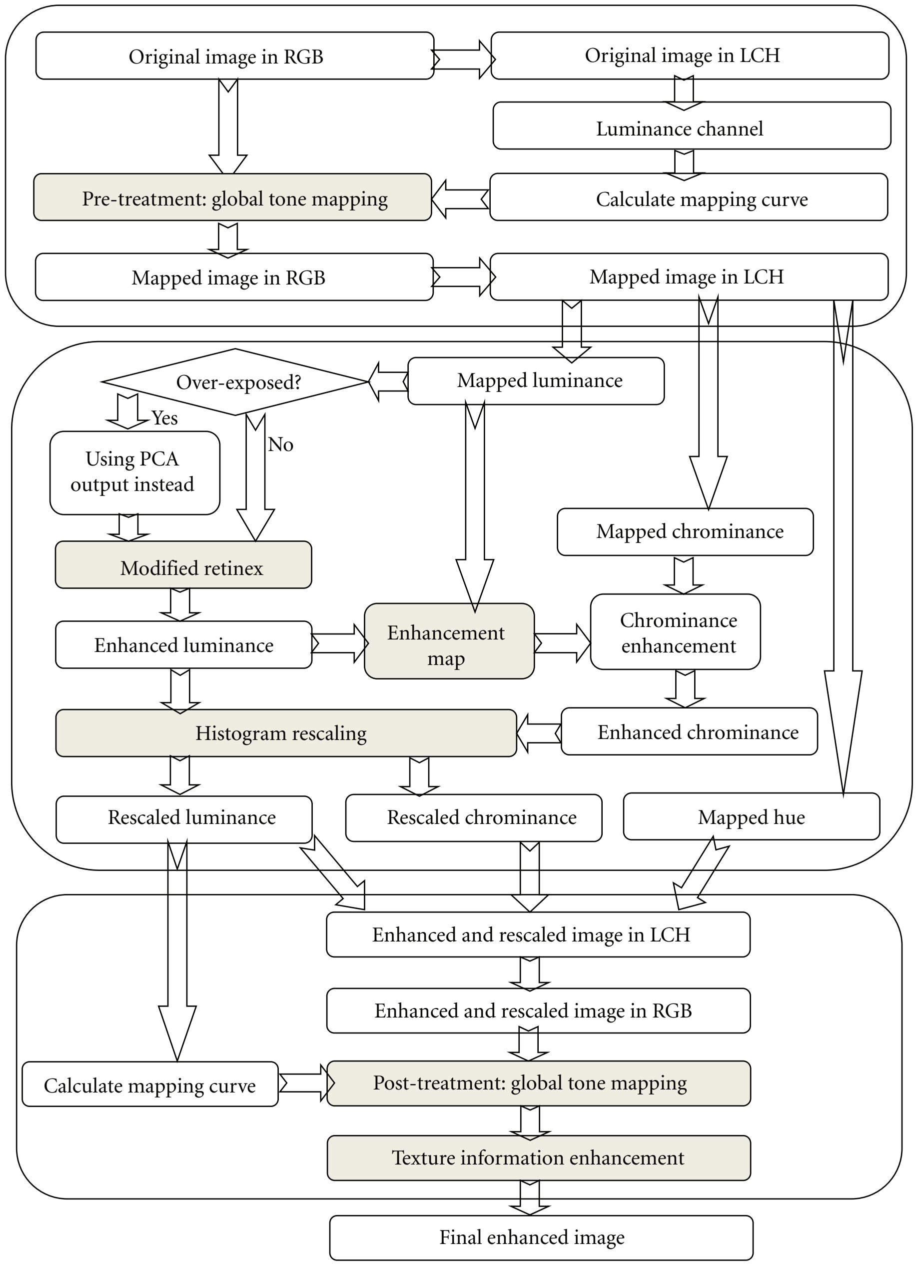


Figure 19: Complete implementation flowchart of NECI.

(d) hue component remains unchanged,

(e) posttreatment using the same principle of global mapping.

(iii) Texture information enhancement using multi-scale decomposition of Cortex Transform.

5. Test Results

Different types of natural images have been tested, and the results obtained confirm an encouraging performance of the proposed method. In this section, some test results are shown below. They are grouped into four categories: low-key images, normal-key images, high-key images, and HDR images.

NECI works well with low-key images. Most of these test images are largely enhanced without modifying light source conditions (light source numbers, projecting orientations, etc.) and no halo effect introduced or blocking effects over-amplified. Some typical examples are shown in Figure 20.

The performance of NECI for middle-key image is moderate since the global mapping step will be omitted for this category of image. The major improvement comes from modified Retinex and histogram rescaling in color space CIELCh and texture information enhancement using Cortex transform. Figure 21 shows the test results for this category.

(a) (b)

Figure 20: Low-key image test. (a) Original images; (b) results of NECI.

As discussed in Section 4, the NECI method adapts also to high-key images because the applied PCA analysis and global mapping can compress the luminance scale to normal key. Some results for this category are shown in Figure 22.

HDR images challenge the most to NECI method due to the nature of this category. Caution must be taken when enhancing dark zone by increasing the luminance and chrominance contrast while keeping the hidden artifact within tolerance. On the other hand, the bright zone has almost saturated in brightness, and any enhancement in luminosity will result in loss of contrast information. The proposed method proved its robustness during the test by enhancing dark regions details while keeping bright zone contrast information. Figures 23(a) and 23(b) give some test results.

6. Conclusions and Perspective Works

An automatic method for Natural Enhancement of Color Image (NECI) is proposed in this paper in order to improve the luminance and chrominance contrast of image while avoiding dramatic white balance changes and artifacts. The proposed method applies four steps of image processing including pretreatment by adaptive global tone mapping using circular curve combined with gamma correction, luminance and chrominance contrast enhancement using modified multi-scale Retinex and histogram rescaling in color space CIELCH, another global mapping step as posttreatment, and finally texture information enhancement using multi-channel decomposition of Cortex Transform.

(a) (b)

Figure 21: Normal-key image test. (a) Original image; (b) result of NECI.

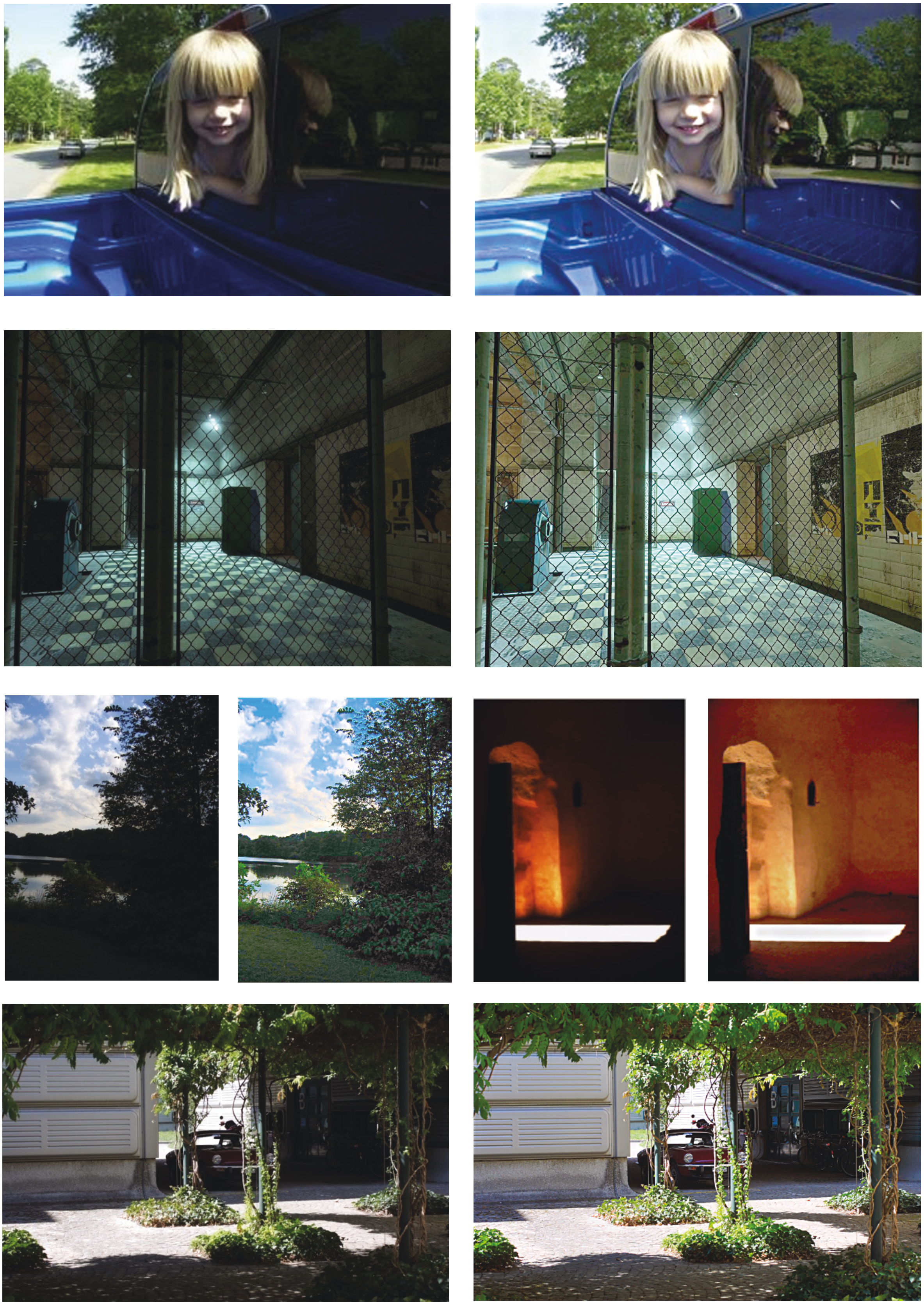
(a) (b)

Figure 22: High-key image test. (a) Original images; (b) results of NECI.

The global mapping algorithm adapts to different image dominant tone, and it is capable of enlightening dark scene or dimming bright scene back to normal-key appearance of images. The modified computational model of multi-scale Retinex increases local luminance contrast with artifact under control. Enhancing chrominance using a reference map calculated from luminance enhancement information generates more balanced enhancement compared to independent channel operation in RGB or LAB color spaces, and histogram rescaling renders image with more natural appearance by eliminating extremely dark or bright points caused by over-enhancement. Last but not least, the details of images which correspond to high-frequency components of images are enhanced by multi-channel decomposition of Cortex Transform.

Albeit with some empirical parameters, the proposed NECI method needs no parameter modification in practice, and its adaptability and robustness are proved by extensive tests and some of them are shown in a previous section.

The time of calculate is not sufficient to be a real-time application due to the complexity of Cortex Transform and contrast calculation. For some unnatural scene images such as medical images, parameters still need to be retrained for a better performance. As far as the HDRI is concerned, the



(a) HDR image test results (Part A). (a) Original images; (b) results of NECI

Figure 23: Continued.

(b) HDR image test results (Part B). (a) Original images; (b) results of NECI

Figure 23

Gaussian Markov segmentation will be integrated to NECI in future works to make different enhancements according to different regions. However, fusion of independently enhanced results will be another open issue.

References

[1] R. C. Gonzalez, R. E. Woods, and S. L. Eddins, *Digital Image Processing*, Prentice Hall, Upper Saddle River, NJ, USA, 2004.

[2] J. J. McCann, "Capturing a black cat in shade: past and present of Retinex color appearance models," *Journal of Electronic Imaging*, vol. 13, no. 1, pp. 36–47, 2004.

[3] E. H. Land, "Recent advances in retinex theory," *Vision Research*, vol. 26, no. 1, pp. 7–21, 1986.

[4] http://dragon.larc.nasa.gov.

[5] R. Sobol, "Improving the retinex algorithm for rendering wide dynamic range photographs," in *Proceedings of the IS&T/SPIE Electronic Imaging Conference on Human Vision and Electronic Imaging (VII '02)*, vol. 4662, pp. 341–348, San Jose, Calif, USA, 2002.

[6] A. Rizzi, D. Marini, L. Rovati, and F. Docchio, "Unsupervised corrections of unknown chromatic dominants using a brownian-path-based retinex algorithm," *Journal of Electronic Imaging*, vol. 12, no. 3, pp. 431–440, 2003.

[7] B. Funt, F. Ciurea, and J. McCann, "Retinex in matlab," in *Proceedings of the 18th IS&T/SID Color Imaging Conference on Color Science, Systems and Applications*, pp. 112–121, 2000.

[8] J. McCann, "Lessons learned from mondrians applied to real images and color gamuts," in *Proceedings of the 7th IS&T/SID Color Imaging Conference on Color Science, Systems, and Applications*, pp. 1–8, Scottsdale, Ariz, USA, 1999.

[9] Z.-U. Rahman, D. J. Jobson, and G. A. Woodell, "Retinex processing for automatic image enhancement," *Journal of Electronic Imaging*, vol. 13, no. 1, pp. 100–110, 2004.

[10] S. Chen and A. Beghdadi, "Natural rendering of color image based on retinex," in *Proceedings of the IEEE International Conference on Image Processing (ICIP '09)*, Cairo Egypt, November 2009.

[11] S. Daly, "The visible differences predictor: an algorithm for the assessment of image fidelity," in *Digital Images and Human Vision*, A. B. Watson, Ed., chapter 14, pp. 179–206, MIT Press, Cambridge, Mass, USA, 1993.

[12] L. Meylan, *Tone mapping for high dynamic range images*, Ph.D. thesis, EPFL, Lausanne, Switzerland, July 2006.

[13] l. Meylan and S. Süsstrunki, "Bio-inspired color image enhancement," in *Human Vision and Electronic Imaging Conference*, vol. 5292 of *Proceedings of SPIE*, pp. 46–56, San Jose, Calif, USA, 2004.

[14] F. Ciurea and B. Funt, "Tuning Retinex parameters," *Journal of Electronic Imaging*, vol. 13, no. 1, pp. 58–64, 2004.