SURROUNDING ADAPTIVE TONE MAPPING IN DISPLAYED IMAGES UNDER AMBIENT LIGHT

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ABSTRACT

In this paper, we propose surrounding adaptive tone mapping in displayed images under ambient light. Under strong ambient light, the displayed images on the screen are darkly perceived by human eyes, especially in dark regions. We deal with the ambient light problem in mobile devices by brightness enhancement and adaptive tone mapping. First, we perform brightness compensation in dark regions using Bartleson-Breneman equation which represents lightness effect on the image under different surrounding illuminations. Then, we perform adaptive tone mapping to reproduce the whole image under various ambient light conditions. Adaptive tone mapping combines human visual characteristics with a tone mapping operation considering ambient light influence. Experimental results demonstrate that the proposed method significantly enhances the readability of displayed images under different surrounding light conditions.

***Index Terms*—**Adaptive tone mapping, ambient light, human visual system, low-level enhancement, mobile display.

1. INTRODUCTION

Mobile displays in smart phones, laptops, and car navigation systems are often used under a diverse range of viewing conditions (ambient lights). Ambient lights cause quality loss in displayed images. In particular, under daylight conditions, the displayed image on the screen is perceived to be dark and washed-out, and the image quality is significantly degraded. This problem brings great inconvenience to users. Thus, ambient light influence has received considerable attention by researchers and display manufacturers. Various hardware techniques have been suggested to solve this problem. One method is to control the backlight unit according to the ambient light using a lux sensor [1], which requires more power even though a higher performance might be achieved. The other method is transflective LCD, which utilizes both ambient light and backlight for displaying images [2]. The backlight is turned on to illuminate under dark conditions, while it is turned off to save power and employs the ambient light under bright conditions. Both methods rely too much on hardware, and are costly and hard to implement. Thus, many software techniques have also been studied by researchers. Monobe *et al*. [3] preserved local contrast of the original image to maintain the same contrast as a dark room. Although they effectively preserved the whole contrast, the computational complexity was high and noise artifacts appeared in the displayed images. Mantiuk *et al*. [4] proposed display adaptive tone mapping that a perception model of human visual system (HVS) under different light conditions was formed based on contrast and contrast sensitivity function (CSF). They obtained the response of HVS for an image on the displays close to the response evoked by the original image. This method effectively enhanced image brightness to solve the darkness problem caused by ambient light, but color appearance was inadequately compensated. Lee *et al*. [5] took display characteristics and practical applications into consideration, and realized their method using several color space transformations. They first utilized an HVS adaptive mechanism for luminance enhancement in the CIE XYZ color space, and then compensated the color gamut in CIE LCH color space.

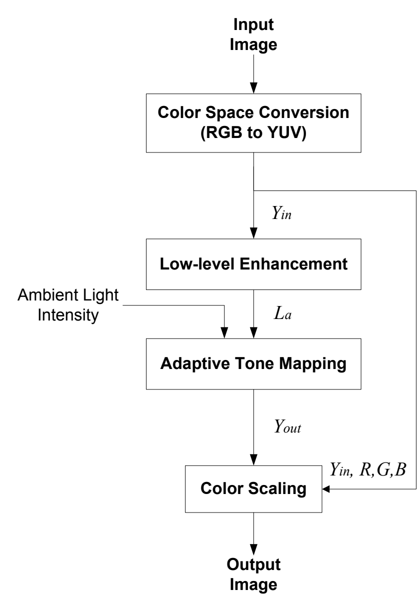


Fig. 1 Whole framework of the proposed method.

This method improved image quality in both brightness and color; however, there is room for improvement in performance. Kim [6] quantified the contrast discrimination ability of human observers under ambient light as a weighting function to determine parts of an image, whatever their spatial frequency appears under a certain ambient condition. He adopted the weighting function as an image enhancement filter in the spatial frequency domain, and enhanced image brightness with high fidelity. Its main reason in mobile displays is as follows: when we move display devices from indoor (weak light condition) to outdoor (strong light condition), our eyes adapt to the change by HVS adaptive mechanism, while displays cannot adapt. After the automatic adjustment, our eyes become sensitive to the strong light from outside, while no longer sensitive to the weak light emitted from displays, thus the screen looks dark. Thus, the most serious problem is darkness in displays, especially when the image itself contains dark regions, it is quite unreadable under strong ambient light. Concerning this issue, we first employ a low-level enhancement method based on Bartleson-Breneman equation [7] to compensate brightness for dark regions. This operation effectively enhances brightness in dark regions such as cast shadows, and compensates for the weakness of their readability. We perform adaptive tone mapping to enhance the contrast of the whole image under various viewing conditions, which considers the influence of the ambient light and HVS characteristics. First, we convert an original RGB image into the YUV color space, and select the Y-component Y_{in}. Then, we perform low-level enhancement to increase dark regions, and obtain the corresponding enhanced image L_a. Similar to the reproduction under various ambient light intensities, we provide adaptive tone mapping for enhancing the whole region in images. Finally, we employ color scaling to retain color information. Fig. 1 illustrates the framework of the proposed method.

2. COLOR SPACE CONVERSION

Given a color image, we first convert the RGB color space to the YUV one. We perform contrast enhancement in the Y-component Y_{in}. RGB color space is transformed into YUV color space as follows:

$$\begin{aligned} Y_{in} &= T(1,1)\cdot R + T(1,2)\cdot G + T(1,3)\cdot B \\ U_{in} &= T(2,1)\cdot R + T(2,2)\cdot G + T(2,3)\cdot B + 128 \\ V_{in} &= T(3,1)\cdot R + T(3,2)\cdot G + T(3,3)\cdot B + 128 \end{aligned} \tag{1}$$

$$T = \begin{bmatrix} 0.2126 & 0.7152 & 0.0722 \\ -0.1146 & -0.3854 & 0.5 \\ 0.5 & -0.4542 & -0.0468 \end{bmatrix} \tag{2}$$

(a) (b) (c)

Fig. 2 Low level enhancement performance. (a) Original input image. (b) Low-level enhanced result. (c) Mapping curve: The *x*-coordinate is the original input intensities Y_{in}, while the *y*-coordinate is the low-level enhanced intensities L_a.

3. LOW-LEVEL ENHANCEMENT

Since objects in the image are under different surrounding illuminations, the captured images often contain both extremely bright and dark regions. If these regions are enhanced equally, bright regions are over-enhanced while the enhancement of dark regions is insufficient. Thus, low-level enhancement is necessary prior to contrast enhancement. We adopt Bartleson-Breneman equation for low-level enhancement [7] which is a set of enhancement equations according to different surrounding illuminations on the image. It first calculates the maximum luminance L_{max} and minimum luminance L_{min} in an image as follows:

$$L_{\max} = 25.83 + 30.82L^{0.6753} \tag{3}$$

$$L_{\min} = 0.0212 + 0.0185L^{1.0314} \tag{4}$$

where L is the luminance intensity of an image. Then, the adaptation luminance L_a under different surrounding illumination is as follows:

$$L_a = I_{gain} f + I_{offset}$$

$$f = \left| \frac{L - L_{\min}}{L_{\max} - L_{\min}} \right|^{\gamma}, I_{gain} = \frac{100}{f_{\max} - f_{\min}}, I_{offset} = -\frac{100 f_{\min}}{f_{\max} - f_{\min}} \tag{5}$$

As shown in Fig. 2, the darker surface of the church is enhanced obviously, and the mapping curve further confirms that low-level enhancement effectively enhances brightness, especially for low-level intensities.

4. ADAPTIVE TONE MAPPING

The ambient light effect on displays is the reflected light *ref* from a display surface, which elevates the luminance of the darkest pixels on a display and reduces the available dynamic range (contrast), thus degrading image quality. We obtain *ref* from ambient light intensity A as follows:

$$ref = r \cdot \frac{A}{\pi} \tag{6}$$

where r is the reflectivity. Ward proposed a tone mapping operator (TMO) m which satisfies as follows [8]:

$$L_d = mL_w \tag{7}$$

where L_w is the luminance seen by the world observer, and L_d is the luminance seen by the display observer. We combine HVS (Ferwerda's cone and rod threshold versus intensity (TVI) function [9]) with Ward's TMO as well as take ambient light influence into consideration, and obtain m as follows:

$$m = t(L_a + ref) / t(L) \tag{8}$$

where L_a is the low-level enhanced result, ref represents the ambient influence, their sum satisfies the concept of L_d, and the original luminance L is similar to L_w. $t(\cdot)$ is Ferwerda's cone and rod TVI functions as follows:

$$\log t(L_a) = \begin{cases} -2.86, & if \log L_a < -3.94 \\ (0.405 \log L_a + 1.6)^{2.18} - 2.86, & if -3.94 \le \log L_a < -1.44 \\ \log L_a - 0.395, & if -1.44 \le \log L_a < -0.0184 \\ (0.249 \log L_a + 0.65)^{2.7} - 0.72, & if -0.0184 \le \log L_a < 1.9 \\ \log L_a - 1.255, & otherwise. \end{cases} \tag{9}$$

We use m for tone mapping and obtain the luminance component Y_{out}.

5. COLOR SCALING

To recover the color information, we use color scaling as follows:

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} ratio & 0 & 0 \\ 0 & ratio & 0 \\ 0 & 0 & ratio \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{10}$$

$$ratio = \frac{Y_{out}}{Y_{in}} \tag{11}$$

We obtain the final output RGB image by multiplying each channel of the input image by *ratio*, where $[R', G', B']^t$ and $[R, G, B]^t$ represent the color components of the output and input images, respectively.

6. EXPERIMENTAL RESULTS

We evaluate the performance of the proposed method on four test images captured by digital camera as shown in Figs. 3 and 4. We use a PC with Intel (R) Core (TM) i3 CPU (2.27GHZ) and 2.00GB RAM running a Windows 7 environment and MATLAB.

A. Visual Comparison

First, we compare the proposed method with three enhancement techniques: the conventional histogram equalization (HE), the weighted thresholded HE (WTHE) [10], and the contextual & variational contrast enhancement (CVC) [11]. The parameters (r, v) in WTHE, (α, β, γ) in CVC are fixed to (0.5, 0.5) and (1/3, 1/3, 1/3), respectively, to provide better results. Fig. 3 compares the contrast enhancement performance. In histogram equalization (HE), undesired artifacts and noises appear and the quality of images is seriously degraded by contrast overstretching, which produces unnatural and visual displeasing results as shown in Fig. 3(b).

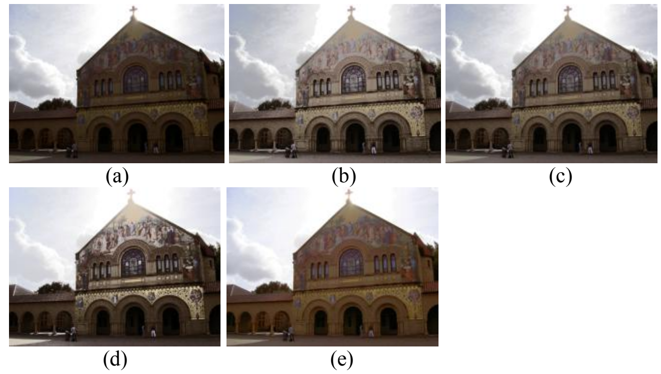
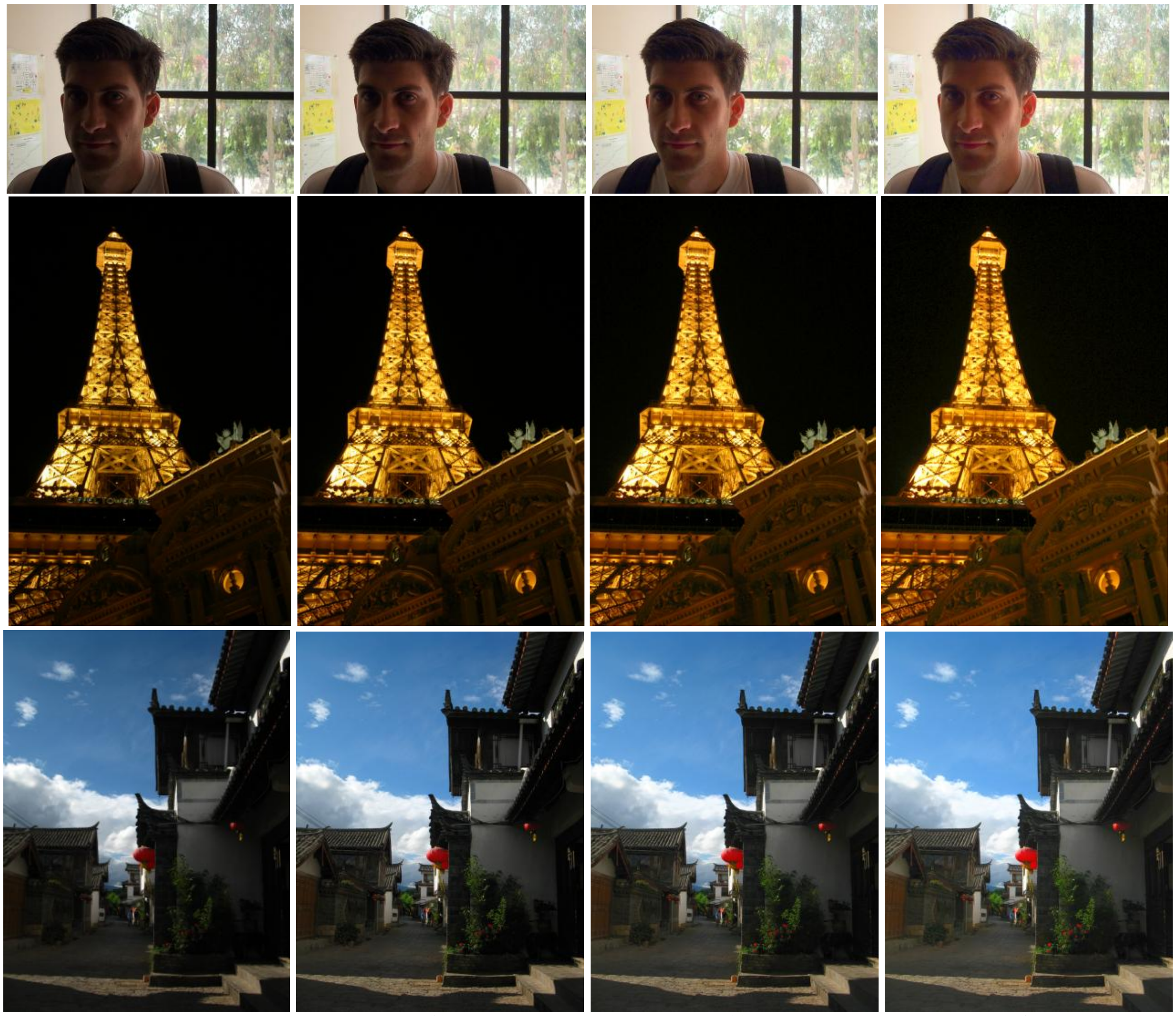


Fig. 3. Visual comparison with existing enhancement methods for *Memorial Church*. (a) Original image, (b) HE, (c) WTHE, (d) CVC, (e) The proposed algorithm.

Weighted Threshold HE (WTHE) [10] is an HE-based enhancement method which binarizes high and low bin values to reduce the HE effect, whereas the results still have drawbacks of HE such as the over-enhancement of the church surface and unnatural color appearance in Fig. 3(c). CVC employs contextual data modeling using a 2-D histogram of an input image to perform nonlinear mapping. However, color distortions and detail loss are detected as shown in Fig. 3(d). In the proposed method, we perform low-level enhancement to compensate brightness for dark regions (e.g. the church wall) based on Bartleson-Breneman equation, and reproduce the whole tone using ambient light adaptive tone mapping. As can be seen in Fig. 3(e), the proposed method provides better visual performance in brightness, contrast, tone, and fidelity than the others.

B. Enhancement under Different Ambient Lights

Fig. 4 shows the performance of the proposed method under ambient light conditions of 500lux, 5000lux, and 10000lux. As ambient light increases, brightness is enhanced obviously, and all perceptual qualities are better than those of the input images as shown in Figs. 4(b)-4(d). The test images often contain both extremely dark and bright regions such as bright background and dark guy in *Guy*, bright tower and dark architecture in *Tower*, and bright sky and dark tiled roofs in *Alley*. If the images are enhanced globally, i.e. we enhance equally for both bright and dark regions, they lose much fine details for bright regions and produce poor enhancement for dark ones. The proposed method effectively solves this problem by low-level enhancement prior to adaptive tone mapping, i.e. improvement of brightness for dark regions. Then, the whole image is reproduced by ambient light adaptive tone mapping. The proposed adaptive tone mapping effectively considers the influence of ambient light, thus achieving adaptive enhancement and tone mapping under various surrounding illuminations.



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

Fig. 4 Results under different ambient light conditions for *Guy*, *Tower*, and *Alley*. (a) Input images, (b) 500lux, (c) 5000lux, (d) 10000lux.

7. CONCLUSIONS

In this paper, we have proposed surrounding adaptive tone mapping in displayed images under ambient light. The proposed method handles dark perception and invisibility on displays under various surrounding illuminations, especially under strong ambient light condition. First, we utilize low-level enhancement based on Bartleson-Breneman equation to achieve brightness compensation in dark regions. Then, we perform ambient light adaptive tone mapping for the whole image considering HVS characteristics and ambient light influence. Moreover, we perform color scaling to generate perceptually good color appearance. Experimental results verify that the proposed method successfully improves the readability of displayed images under various ambient light conditions.

8. ACKNOWLEDGEMENT

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