ADAPTIVE ENHANCEMENT OF LUMINANCE AND DETAILS IN IMAGES UNDER AMBIENT LIGHT

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ABSTRACT

Image quality of mobile displays are significantly influenced by ambient light. In the daylight condition, displayed images on mobile displays are darkly perceived by human visual system (HVS), which suffer from significant detail loss. However, only luminance enhancement seriously affects image details especially for bright regions. To overcome this problem, we propose a quadratic optimization framework which includes data term for luminance enhancement and gradient term for detail enhancement. In the data term, we provide an ambient light nonlinear intensity-transfer function for adaptive luminance enhancement depending on display properties, ambient light, and image contents. In the gradient term, Weber's law is employed for detail enhancement. Finally, we achieve both luminance and detail enhancement by solving the optimization framework. Experimental results demonstrate that the proposed method remarkably enhances the visibility of displayed images under strong ambient light.

Index Terms—Display enhancement, ambient light, detail enhancement, human visual system, luminance enhancement, mobile displays, Weber's law.

1. INTRODUCTION

Mobile displays such as liquid crystal displays (LCDs) play an important role in our daily life. Many display manufacturers concentrate on improving display properties to get good visual quality, but viewing condition changes still degrade the visual quality in mobile displays [1]. Above all, ambient light causes severe degradation of the visibility in mobile displays. In this work, we consider ambient light as a key viewing condition factor in mobile environment. Due to the reflected light emitted from display screens and the adaption of HVS on them, ambient light causes degradation of displayed images in color, luminance, and contrast. For compensating image distortions in color appearance, CIECAM 97s [2] and CIECAM02 [3] have been developed which includes a series of perceptual effects and predicts color appearance under ambient light. However, these two models need to determine many viewing condition parameters and are complicated to implement. In recent years, many studies focus on compensating perceived luminance or contrast distortion based on the HVS model. Lee et al. [4] introduce an S-shaped Naka-Rushton equation [5] for luminance adjustment and chroma compensation for color distortion. This method achieves bright and colorful image but introduces the color cast problem. Mantiuk et al. [6] combine ambient light HVS model with HDR tone mapping problem and realize ambient light tone mapping by minimizing visual distortion based on the HVS model. Despite displayed image can be adjusted based on display properties and ambient light, an image appears foggy and loses details. Aydın et al. [7] apply maladaptation and temporal recovery of sensitivity mechanism to previous HVS model. This model has been used for visibility and detail loses prediction in the car interior display under varying lighting conditions. Kim et al. [8] develop adjusted surround luminance contrast sensitive function (CSF) and then uses the CSF as filter to automatically enhance images on small sized mobile LCD. Cheng and Yang [9] propose a multi-scale decomposition based method to compensate perceived image contrast in different local bands by using the same CSF. These surrounding CSF-based methods can compensate perceived contrast, but their overall brightness is not enough for enhancement. Thus, the displayed image is still darkly perceived under high ambient light.

Based on the former analysis, current methods mainly focus on compensating contrast distortions. However, ambient light does not only lead to contrast distortions but also luminance distortions. Especially, in the strong ambient light, luminance distortions are more important than contrast distortions. In this paper, we start from two observations in our daily life that ambient light affects displayed images: 1) Reduction of perceived luminance called dark perception; 2) Loss of image detail related to contrast distortions. We propose a quadratic optimization framework to compensate these distortions simultaneously. Inspired by Bhat et al. [10], the optimization framework is as follows:

$$\iint \left(f(x,y) - d(x,y) \right)^2 + \lambda \left\| f(x,y) - \mathbf{g}(x,y) \right\|^2 dxdy \quad (1)$$

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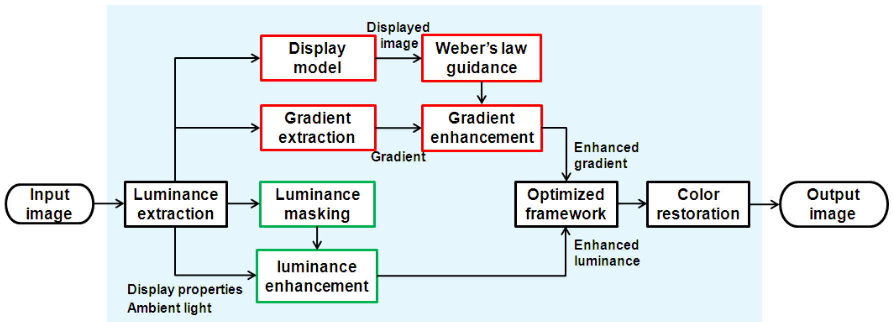


Fig. 1 The proposed framework of ambient light adaptive display enhancement.

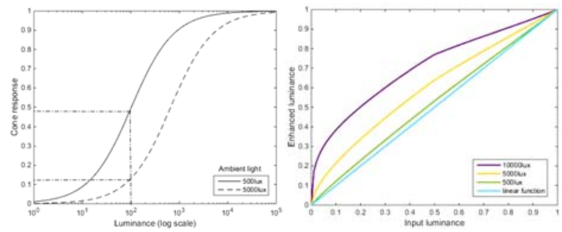
where $d(x,y)$ is the data term for enhancing luminance, $g(x,y)$ is the gradient term for enhancing gradient under ambient light, and λ balances between two terms. In the data term, we present an ambient light adaptive nonlinear intensity-transfer function to enhance luminance in images. In this function, adaptive enhancement depends on ambient light, display properties, and image contents. In the gradient term, Weber's law is introduced to obtain the gradient gain factor under different ambient light, which achieves desired gradient of images to enhance lost details. Then, we produce contrast enhancement results by solving the optimization framework. Finally, we achieve color enhancement on the results by color restoration. Thus, we significantly improve the readability of displayed images under strong ambient light without elevating backlight, which can save power consumption. The framework of the proposed method is illustrated in Fig. 1.

2. ADAPTIVE LUMIANCE ENHANCEMENT FOR DESIRED IMAGE LUMINANCE

In this section, we first show why ambient light causes dark perception of displayed image by HVS response model. Then, we provide an ambient light nonlinear intensity-transfer function to obtain enhanced image luminance d(x,y). Naka-Rushton equation [4] [11], one of HVS response models, shows that the HVS response severely decreases with the increase of ambient light as shown in Fig. 2(a). It can be observed that 1) with the increase of ambient light, perceived luminance distortions gradually become dominant; 2) distortions in dark regions are more serious than those in bright regions.

According to two observations, we propose an ambient light nonlinear intensity-transfer function which follows two principles: 1) luminance enhancement degree rises with the increase of ambient light; and 2) enhancement in the dark region is more than that in the bright region. Thus, given the input image, the adaptive enhancement in luminance under ambient light is obtained as follows:

$$L_e(x,y) = \left(L(x,y)\right)^{i+(1-i)\cdot s(x,y)} \tag{2}$$



(a) (b)

Fig. 2 (a) The cone response of displayed image on mobile display under ambient light 500lux (solid line) and 5000lux (dash line). We assume that the maximum luminance is 100cd/m^2. It can be observed that maximum response decreases from 0.48 to 0.12 when mobile display moves from indoor (500lux) to outdoor environment (5000lux); (b) Proposed adaptive function under different ambient light: 500lux, 5000lux and 10000lux.

$$s(x,y) = L(x,y)\cdot T(x,y) \tag{3}$$

where $L(x,y)$ is original image, $L_e(x,y)$ is enhanced image, and i controls the maximum enhancement degree according to ambient light. It is calculated from display properties, ambient light E_{amb}, and HVS response in the indoor R_{indoor} by Naka-Rushton equation [11] as follows:

$$i = \frac{(\log(L_{max}+L_{refl}) - \log(L_{black}+L_{refl}))}{\log(f_{\max}(\mathrm{R}_{indoor})) - \log(f_{\min}(\mathrm{R}_{indoor}))} \tag{4}$$

$$L_{refl} = \frac{k}{\pi}E_{amb} \tag{5}$$

where f_{max} and f_{min} determine maximum and minimum value. L_{max} and L_{black} are peak luminance and black level of display. L_{refl} represents the reflected light intensity and k is the display reflectivity. Adaptive enhancement degree $s(x,y)$ for each pixel is determined by image luminance $L(x,y)$ and background luminance masking factor $T(x,y)$. $L(x,y)$ can make more enhancement in dark region than in bright region. $T(x,y)$ represents normalized visibility threshold developed by background luminance masking in JND model [12]. $s(x,y)$ only by $L(x,y)$ will lead to large enhancement of dark region, which result in over enhanced artifact and make enhanced image tone look unnatural as shown in Fig. 3(b). Thus, we introduce $T(x,y)$ to avoid the over-enhancement problem as shown in Fig. 3(c). Adaptive nonlinear intensity-transfer function under ambient light is shown in Fig. 2(b).

(a) (b) (c)

Fig. 3 Luminance enhancement by different nonlinear intensity-transfer function and enhanced color image is obtained by color restoration. (a) Original image. (b) Adaptive function by image luminance: $L_e=L^{i+(1-i)*L}$. (c) Proposed adaptive function $L_e=L^{i+(1-i)*L*T}$ (Ambient light: 10000lux).

(a) (b) (c)

Fig. 4 The enhanced image gradient under different ambient light. (a) original image gradient (b) 500lux (c) 10000lux.

(a) (b)

Fig. 5 (a) six test images (from left up to right bottom): *Hat*, *Window*, *Alley*, *Forest*, *Guy*, and *Flower*. (b) Experimental set-up including photographic lamp, tablet, and lux sensor.

3. AMBIENT LIGHT IMAGE GRADIENT ACQUIREMENT BASED ON WEBER'S LAW

We first introduce weber's law to analyze displayed image detail distortion, and then apply it to manipulate image gradient for enhancing image detail. Before weber's law, we need to discuss the influence of ambient light on displayed image luminance $L_d(x,y)$ by introducing display model [6]:

$$L_d(x,y) = L(x,y)^{\gamma} \cdot (L_{max} - L_{black}) + L_{black} + L_{refl} \tag{6}$$

where $L(x,y)$ is image pixel and γ is display gamma (usually is 2.2). L_{max}, L_{black} and L_{refl} are the same as Eq.4 and 5. It can be seen from Eq.6 that ambient light boosts displayed image luminance by adding reflected light from display screen. And weber's law shows that just noticeable distortion (ΔL) increases when background luminance (L_a) does:

$$\frac{\Delta L}{L_a} = C \tag{7}$$

It is concluded from weber's law and display model that with ambient light increasing, displayed image luminance becomes larger and detection threshold (i.e. JND) also increases. Thus the luminance difference (i.e. gradient) should be enhanced increasingly. The conclusion is introduced to design gradient gain factor for manipulating image gradient. Then desired image gradient is obtained by manipulating original image gradient:

$$\mathbf{g}(x,y) = \nabla\mathbf{L}(x,y)\, s(x,y) \tag{8}$$

where $\mathbf{g}(x,y)$ is desired image gradient under ambient light; $\nabla\mathbf{L}(x,y)$ is original image gradient; and $s(x,y)$ represents gradient gain factor, which follows two principles: 1) gradient should be enhanced increasingly with ambient light increasing; 2) gradient gain factor should adaptively magnify more in the low gradient region than in the high gradient one because of limited display dynamic range. Thus, the gradient gain factor $s(x,y)$ can be calculated by exponential function and its base term focuses on enhancement of low gradient region. Its exponential term determines enhancement level by considering background luminance of displayed image, which depends on weber's law:

$$s(x,y) = \left(\frac{\max \|\nabla L(x,y)\|}{\|\nabla L(\mathrm{x,y})\| + \varepsilon} \right)^{t(x,y)} \tag{9}$$

where $\|\nabla L(x,y)\|$ is gradient magnitude of original image, $\max\|\nabla L(x,y)\|$ is maximum gradient magnitude, ε is small positive constant, and $t(x,y)$ is normalized background luminance of displayed image $L_d(x,y)$ by Eq. (6).

Background luminance was considered to be weighted average over 8 neighbors (see details in [13]). The enhanced image gradient under different ambient light has been shown in Fig. 4.

4. NUMERICAL SOLUTION AND COLOR RESORTION

Given desired image luminance $L_e(x,y)$ and desired image gradient $g(x,y)$ under ambient light, the resulted image can be obtained by minimizing the optimized framework as shown in Eq. (1). Since our framework is quadratic, many weighted least-squares techniques can solve it [10]. In this paper, we adopt the conjugate-gradient method to solve it. Finally, we generate color images by the Schlick's method [14] as follows:

$$M_e(x,y) = M_o(x,y)\left(\frac{L_e^{'}(x,y)}{L_o(x,y)}\right)^{\gamma} \tag{10}$$

where $M_e(x,y)$ and $M_o(x,y)$ are trichromatic channel value of enhanced color image and original image; $L_e^{'}(x,y)$ and $L_o(x,y)$ are enhanced image after solving the optimized framework and original image; and γ varies between 0.6 and 0.8.

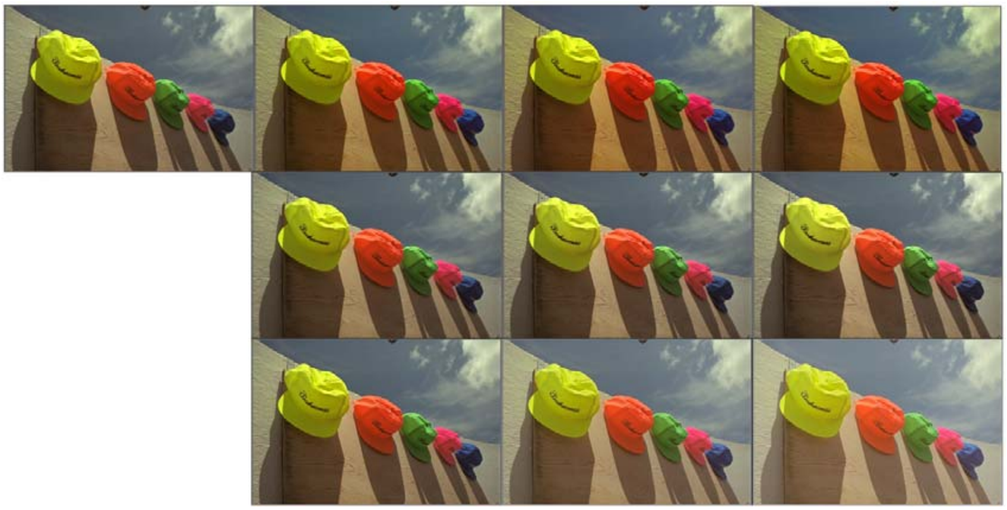
5. EXPERIMENTAL RESULTS

In the following experiments, we verify that the proposed method enhances both luminance and details of displayed images under varying ambient light. The main goal of the proposed method is to produce brighter images with more visible details. Moreover, the proposed method improves the readability of images without backlight elevation, which can save power consumption. Test images are from the Kodak lossless true color image suite [15], and captured by digital camera as shown in Fig. 5 (a). The resulted images are displayed on Samsung GALAXY Tab ST700, which maximum luminance L_{max}=544cd/m^2 and the reflectivity is 4.7% from Displaymate website [16].

TABLE I
AVERAGE SCORES OF THE PROPOSED, LEE'S [4], AND KIM'S METHODS [8]

500lux				5000lux				10000lux			
[4]	[8]	Proposed	Original	[4]	[8]	Proposed	Original	[4]	[8]	Proposed	Original
1.5	0.8	**3.3**	0.5	0.4	0.2	**5.0**	0.2	0.6	0.6	**4.8**	0

Bold numbers represent the best performance in each ambient light.



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

Fig. 6 Experimental results in *Hat*. (a) Original image. (b)-(d) Enhanced color images under 500lux, 5000lux, and 10000lux, respectively. From the first row to last row: resulted images from Lee's method [4], Kim's method [8], and the proposed method, respectively.

The photographic lamp (DOF LED-1000) projects light onto the middle of table as ambient light. The lux sensor is TES 1332A, which can measure ambient light intensity in lux. The experiment set-up is shown in Fig. 5(b). For the tests, we use a PC with Intel (R) Core (TM) i5 CPU (2.60GHZ) and 4.00GB RAM running a Windows 7 environment and MATLAB. Ten observers participate in the subjective experiments. The proposed method and other two comparative algorithms are tested under different ambient light, i.e. 500lux, 5000lux and 10000lux. The parameter λ in our method is set to 0.1. The maximum luminance of tablet is set 100cd/m^2 and auto-brightness function should be closed in the experiments. Each person should choose which enhanced image looks brighter, more visible details and better visual quality from four compared images under one ambient light. The three compared images are generated from proposed method, Lee's method [4], Kim's method [8] and the rest of compared image is original image. The total number of experiments are 6 test images×3 ambient light = 18 times. The average score, which means the number of selected times for each method, is computed and summarized in TABLE I. From the first and second row of Fig. 6, Lee's method can make image looks brighter and colorful by increasing image chroma because of the saturation effect in the color appearance model. Kim's method [8] compensates contrast sensitivity distortion between different ambient lights by surrounding CSF. Thus, the two methods can preserve image contrast in the mid-tone region. In the low ambient light (i.e. 500lux), observers choose Lee's [4] or Kim's [8] method because ambient light has small influence of perceived image luminance and image contrast is preserved. However, with the increase of ambient light, the perceived luminance distortion gradually becomes dominant as discussed in Section 2. The proposed method focuses on compensating perceived luminance distortions. Therefore, in 5000lux and 10000lux, the proposed method performs much better than the other two ones. Moreover, the proposed method can also reduce detail distortions compared with the Kim's method [8] which contrast and detail distortion appears in the bright region.

6. CONCLUSIONS

In this paper, we have proposed an optimization framework which achieves both luminance and detail enhancement based on the observations that ambient light causes luminance and detail distortions in displayed images. We have provided an ambient light nonlinear transfer function to compensate luminance distortions. We use Weber's law to enhance image gradient for reducing detail distortions. Experimental results demonstrate that the proposed method successfully enhances the visibility of displayed images without elevating backlight. In the future, we will investigate the effect of ambient light on the color gamut, and reproduce natural colors in mobile displays.

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