VISIBILITY ENHANCEMENT VIA OPTIMAL GAMMA TONE MAPPING FOR OST DISPLAYS UNDER AMBIENT LIGHT

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ABSTRACT

Visibility of the overlaid virtual image is sensitively affected by surrounding illumination in OST (optical see-through) displays. Ambient light may especially deteriorate the visibility of low gray levels, whose luminance is comparable to ambient light. Therefore, we first derive a luminance model based on actual measurements under various ambient lights, and use this model to extract low gray-level region (LGR), which suffers severely from contrast loss. It was experimentally found that gamma tone mapping is the most appropriate for LGR contrast enhancement of OST displays. The gamma value is optimally determined by cost minimization. Visibility enhancement is verified by experiments on a practical setup with a variety of ambient light levels and images.

Index Terms— *ambient light, OST display, visibility enhancement, low gray-level region, gamma tone mapping*

1. INTRODUCTION

AR (augmented reality)-capable devices often make use of transparent displays, and this makes them sensitive to the effect of surrounding illumination. Therefore, visibility of the overlaid virtual content becomes a crucial issue. Figure 1 illustrates the phenomenon of visibility reduction at an OST display, which commonly occurs in indoor and outdoor environments.

A few research works deal with visual quality enhancement of OST displays, but most of them address the issue of color correction [1]-[4]. Although there have been contrast enhancement works in the similar field of direct-projected augmented reality, there is no explicit visibility enhancement work for OST displays yet.

Park et al., in the context of direct-projected augmented reality, proposed a contrast enhancement method [5]. They try to preserve the contrast-enhanced colors as similar as possible to the original input by preserving hue and saturation. Yet, it does not address the issue of contrast degradation as ambient illumination gets stronger.

A number of papers proposed interesting applications using OST-HMDs (optical see-through head mounted displays). Hu et al. proposed a visual aid application for nyctalopia or dark environments where it is difficult to recognize objects [6]. They made use of an external camera to capture a real scene, and enhanced its visibility (rather than the virtual content). Although there is no visibility enhancement work for OST-HMD itself, there have been a number of works that enhance the visibility of conventional flat panel displays. We previously proposed a method for both contrast enhancement and power reduction for mobile LCD displays [7]. This work minimized the contrast loss resulting from backlight dimming of an LCD, which is adaptively controlled according to input images. Both LCD backlight dimming and the influence of ambient light on OST displays have a similar effect of dynamic range reduction, which consequently results in contrast loss. However, contrast loss induced by backlight dimming is different from contrast loss by ambient light in terms of its characteristics, which needs to be dealt with differently. Moreover, [7] does not consider visibility reduction from ambient illumination. This work is an application of our previous work to a new type of display, OST.

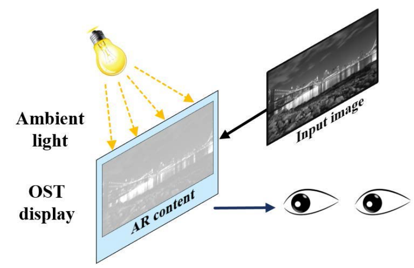

Fig. 1. Visibility reduction of OST display under ambient light

In this paper, we propose an image compensation method in order to improve the visibility of OST displays under varying lighting conditions. We first derive a luminance model based on actual measurements on OST displays. Given an input image of OST-HMD, the contrast loss image (induced by surrounding lights) is first estimated based on the luminance model. Close observation of the OST-HMD revealed that low gray-level region (LGR) of an image is strongly affected by ambient light in particular, leading to visibility reduction. Average contrast loss at LGR appears to be over twice as large as that of the overall image, as confirmed by Fig. 5. Therefore, it is appropriate to use the gamma tone mapping curve among a couple of tone mapping ones for contrast enhancement. To determine an optimal gamma value, we establish an objective function to reflect the contrast loss. Practical experiments with OST-HMD demonstrate that the proposed method can increase the visibility of OST displays adaptively to ambient lighting conditions.

This paper is organized as follows. Section 2 describes contrast loss at LGR induced by ambient light. Section 3 derives a measurement based luminance model for OST displays, and establishes a cost function for optimal visibility enhancement. In section 4, the effectiveness of the proposed contrast enhancement is verified visually and quantitatively. Section 5 concludes the paper.

2. CONTRAST LOSS INDUCED BY AMBIENT LIGHT

There have been works that relieve the contrast loss induced by LCD backlight dimming. LCD backlight dimming reduces the maximum display luminance, which lowers average picture level (APL) and induces contrast loss. To overcome this problem, darker pixels are linearly increased to compensate for the reduced brightness and

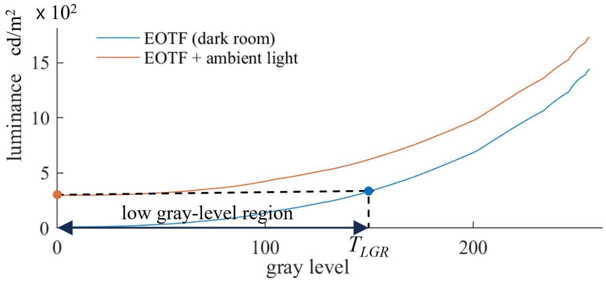

Fig. 2. Estimation of low gray-level region under ambient light

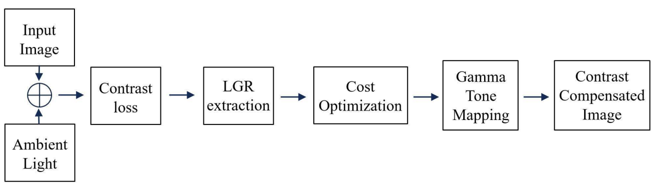

Fig. 3. Flowchart of the proposed LGR visibility enhancement

contrast. Brighter pixels are shrunk to be fitted in the remaining dynamic range [7]. This kind of linear tone mapping and brightness compensation are appropriate for the situation where the dynamic range is reduced by the reduction of maximum luminance. Meanwhile, ambient light causes dynamic range reduction of OST displays in a different manner. Because ambient light is added to the OST display output, the brightness of dark pixels is increased. This results in an irreversible dynamic range reduction, because even if the OST input pixels are set to zero, there will be brightness resulting from ambient light. In this case, the brightness of dark pixels cannot be further reduced physically. The appropriate treatment is to stretch the luminance range occupied by dark pixels so that visible contrast may be achieved even with brightness provided by ambient light.

OST-HMD, like other displays, has an EOTF (Electro-Optical Transfer Function) in the form of a power function. EOTF denotes the non-linear transformation between input pixel levels and the output luminance of a display perceptible to users. Ambient light adds luminance to the display output and changes the perceived luminance curve of the user to deviate from the display EOTF. Although the luminance of all pixel levels increases in general, the primary problem is that black levels on the OST-HMD seem to be much brighter. Under ambient light, low gray levels of the displayed image (comparable to ambient light in terms of luminance) become hardly discernible. In this paper, we denote the image region composed of such low gray levels as LGR, which suffers from severe contrast loss.

Theoretical studies of the behavior of human visual system support that humans perceive contrast loss on LGR more strongly than on non-LGR. A behavior of human visual perception is that humans are more sensitive to changes in lower stimulus rather than higher one, according to Weber-Fechner law [8]. This indicates that humans are more sensitive to contrast loss in LGR, as the overall luminance increase of low gray levels is felt to be dramatically greater than that of high gray levels.

As illustrated in Fig. 2, under diverse ambient lights, black levels on OST displays are not expressed sufficiently as true black. Namely, dynamic contrast ratio becomes much poorer as ambient light gets stronger. Especially, it is hard to tell the difference between OST display pixels whose luminance is lower than ambient

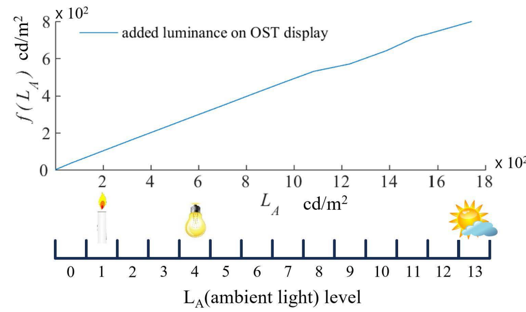

Fig. 4. ***(top)*** **The increase of OST display luminance under varying ambient light,** ***(bottom)*** **Relative scale of ambient light**

light. Therefore, contrast enhancement at LGR is important for OST display visibility under ambient light.

Motivated by the above observations, we attempt to maintain the visibility of OST-HMD as high as possible by minimizing contrast loss at LGR. To this end, we derive the user-perceived luminance model, based on actual measurements, and the LGR is extracted using the model. Then, we quantitatively estimate the amount of contrast loss reduction induced by ambient light, which is used to compensate the input image for visibility enhancement.

3. PROPOSED VISIBILITY ENHANCEMENT METHOD

Figure 3 shows the overall flow chart of the proposed method. The contrast loss image is estimated on the luminance domain, based on the model of user-perceived luminance. Then, LGR is found from the contrast loss image, and contrast loss is quantitatively estimated. LGR contrast loss, found in this manner, constitutes an objective cost function where gamma tone mapping is adopted for contrast enhancement. An optimal gamma value for contrast enhancement is found by minimizing this cost function with respect to gamma.

3.1. Modeling the effect of ambient light on the luminance of OST display

To simulate the contrast loss of an image, the display EOTF and ambient light need to be characterized. The image pixel is converted to its luminance on the display by EOTF. By combining the influence of ambient light with the EOTF, the visibility-reduced image can be easily simulated as follows.

$$Y(x, L_A) = EOTF(x) + f(L_A) \tag{1}$$

where x is an input pixel, and L_A is the level of ambient light. The function f in (1) represents the influence of ambient light on luminance of an OST display. The output Y in (1) is a model estimate of the user-perceived luminance, given an input pixel x and ambient light L_A. Applying this model to the input image, the visibility-reduced image is simulated easily. Note that when $L_A = 0$ (dark room), $Y(x, L_A)$ corresponds to the intrinsic EOTF of an OST display which is invariant of surrounding light L_A. When $L_A > 0$, $Y(x, L_A)$ increases with the ambient light level. Figure 4, *top*, shows the amount of the increased luminance actually measured under our experimental setup. With this luminance boosting, the user perceives the display image as if the OST display EOTF has changed.

Fig. 5. Contrast reduction comparison of LGR vs. non-LGR

Therefore, based on the measurements of Fig. 4, *top*, we can establish a user-perceived luminance model, $Y(x, L_A)$. It is complex to model ambient light L_A. However, assuming a function f, which estimates the influence of ambient light on the OST display, a simplified additive model can be derived as in (1). Figure 4, *bottom* shows the relative scale of ambient light levels. Level 0 in L_A corresponds to dark room, and higher level means brighter illumination. Roughly, the level 4 is similar to indoor fluorescent ~~lights~~ while the level 13 is comparable to outdoor daylight. Various lighting scales are simulated from dark room to sun light.

It is difficult to model the influence of nearby light sources on the OST display accurately. Therefore, we assume a fairly approximated model, the ambient light model. The influence of a light source on a display is measured by the amount of light incident to the OST display from the front-facing direction. Although an ambient light source emits the fixed amount of light, its amount arriving at the display greatly varies, depending on the location of the source and surrounding structure. Thus in this paper, it is assumed that an ambient light source is stationary and its intensity is known in advance. Since the intensity of ambient light can be rather simply obtained by sensors (which manufacturers of the OST-HMD can integrate into their products) the two assumptions do not make the proposed method impractical.

3.2. Extracting Low Gray-level Region (LGR)

As explained in previous Section 2, the contrast loss at LGR largely affects visibility. Therefore, the LGR needs to be determined. Figure 5 shows an example of LGR when L_A = 12. The average contrast loss on LGR is almost twice larger than non-LGR.

Given the ambient light and LGR, X_{CL_LGR}, the LGR of the contrast loss image, is obtained by masking the contrast loss simulated image, X_{CL} with the LGR mask as follows.

$$X_{CL\_LGR} = X_{CL} \circ X_{mask} \tag{2}$$

where $\circ$ denotes the Hadamard or entry-wise product, X is an input gray level image and X_{mask} is an indicator of LGR pixel locations. X_{mask} is simply obtained by thresholding the contrast loss simulated image, X_{CL} by T_{LGR}. Note that X_{CL} is the contrast loss image simulated by the user perceived luminance model. T_{LGR} is a threshold which LGR is less than as illustrated in Fig. 2.

3.3 Gamma tone mapping for LGR contrast enhancement

Gamma tone mapping, based on the power law of human brightness perception [10], transforms linear intensity levels according to a power law so that the encoded intensity levels appear perceptually uniform to humans. Gamma tone mapping is expressed by

$$X_{cor} = (X_{org})^{\gamma} \tag{4}$$

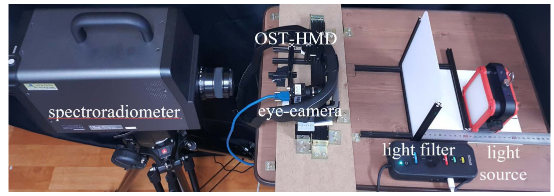

Fig. 6. Experimental setup

Note that high gray levels are stretched for gamma > 1 while low gray levels are stretched for gamma < 1. Therefore, gamma tone mapping with gamma < 1 is an appropriate way of image compensation well suited for counter-acting the contrast loss induced by ambient illumination.

3.4. The proposed objective cost function

Throughout experiments, we identified that gamma tone mapping is the most appropriate for OST displays under ambient light. A cost function is formulated to determine the optimal gamma value in (4) for varying ambient lights. When an LGR is small, a contrast loss region is proportionally reduced. This means there is little need to stretch low gray levels. In this case, gamma should be close to one, to preserve the contrast of the original image. Conversely, when an LGR is large, the contrast of low gray levels is severely reduced. In this case, by setting the gamma to be much smaller than one, the visibility of LGR can be greatly improved.

The optimal gamma can be found by trading-off contrast loss and luminance deviation from the original image. The rationale for this trade-off is the following; Firstly, the overall luminance of the compensated image should be similar to the original image. If not, the compensated image may have discrepancies with the original. Secondly, the contrast of the compensated image should be similar to the contrast of the original image. The contrast loss of LGR should be minimized such that LGR should be kept visible.

Accurate measurement of contrast in an image is a challenging problem. Thus, contrast reduction, instead of absolute contrast, is measured. The Rizzi [9] contrast metric is adopted to measure the contrast reduction of the gamma corrected LGR to original LGR contrast.

The two undesirable discrepancies are jointly formulated as a cost function to be minimized as follows.

$$\begin{aligned} \arg\min_{\gamma} \ & \sum_{i,j} \left\| \frac{Y(x^{(i,j)}, L_A) - Y((x^{(i,j)}, L_A))^{\gamma}}{Y(x^{(i,j)}, L_A)} \right\|^2 \\ & + \lambda \left\| \frac{Rizzi(x_{LGR}) - Rizzi(x_{CL\_LGR})^{\gamma}}{\sum \left| x_{CL\_LGR} \right|} \right\|^2 \end{aligned} \tag{5}$$

In this manner, the gamma for visibility enhancement of OST-HMD is determined adaptively to ambient light.

4. EXPERIMENTAL SETUP & RESULTS

4.1. Experiment environment

Our experimental setup comprises the EPSON BT-2000 OST-HMD. To measure the luminance of display pixels, we use the KONICA

Table 1. Optimal gamma values under varying ambient light, found by the proposed method

	category 1 (large LGR, high detail)													category 2 (large LGR, low detail)					category 3 (small LGR, medium detail)			
	img_1	img_2	img_3	img_4	img_5	img_6	img_7	img_8	img_9	img_10	img_11	img_12	img_13	img_14	img_15	img_16	img_17	img_18	img_19	img_20	img_21	img_22
APL	84.61	43.04	64.72	97.68	84.13	52.95	83.03	95.89	100.53	84.13	75.88	53.40	99.57	113.99	116.59	77.99	62.31	41.33	119.02	115.19	118.04	100.02
L_A level 1	1	1	1	1	1	1	1	1	1	1	1	0.9	1	1	1	1	1	1	1	0.95	1	1
L_A level 2	1	0.95	1	1	1	1	1	1	1	1	1	0.9	0.9	1	1	1	1	1	1	1	1	1
L_A level 3	1	0.8	1	0.85	0.95	1	1	0.9	0.9	0.95	1	0.8	0.7	0.95	1	1	1	1	1	1	1	1
L_A level 4	1	0.7	1	0.65	0.95	1	0.95	0.75	0.75	0.95	1	0.75	0.6	0.9	0.95	1	1	1	1	1	1	1
L_A level 5	1	0.65	0.95	0.6	0.95	1	0.8	0.65	0.65	0.95	0.95	0.7	0.55	0.85	0.85	1	1	1	1	1	1	1
L_A level 6	0.95	0.55	0.85	0.55	0.85	0.85	0.7	0.6	0.55	0.85	0.8	0.7	0.55	0.8	0.8	1	1	1	1	1	1	1
L_A level 7	0.85	0.5	0.8	0.55	0.85	0.75	0.6	0.55	0.45	0.85	0.7	0.65	0.55	0.8	0.8	0.95	0.9	0.95	1	1	1	1
L_A level 8	0.75	0.5	0.7	0.5	0.85	0.7	0.5	0.5	0.4	0.85	0.6	0.65	0.5	0.75	0.75	0.8	0.85	0.95	1	1	1	0.95
L_A level 9	0.65	0.45	0.65	0.5	0.85	0.65	0.35	0.45	0.3	0.85	0.5	0.6	0.5	0.75	0.75	0.7	0.75	0.9	0.9	1	1	0.85
L_A level 10	0.6	0.4	0.6	0.5	0.85	0.55	0.3	0.45	0.2	0.85	0.45	0.6	0.5	0.75	0.7	0.6	0.7	0.85	0.85	1	1	0.85
L_A level 11	0.45	0.35	0.5	0.4	0.75	0.5	0.35	0.4	0.25	0.75	0.35	0.6	0.45	0.7	0.65	0.45	0.55	0.75	0.65	0.95	0.95	0.7
L_A level 12	0.35	0.3	0.4	0.4	0.65	0.4	0.35	0.35	0.25	0.65	0.25	0.55	0.45	0.65	0.65	0.3	0.45	0.7	0.5	0.9	0.8	0.55
L_A level 13	0.3	0.2	0.3	0.3	0.5	0.3	0.4	0.25	0.3	0.5	0.35	0.5	0.4	0.65	0.6	0.35	0.4	0.65	0.35	0.8	0.65	0.3

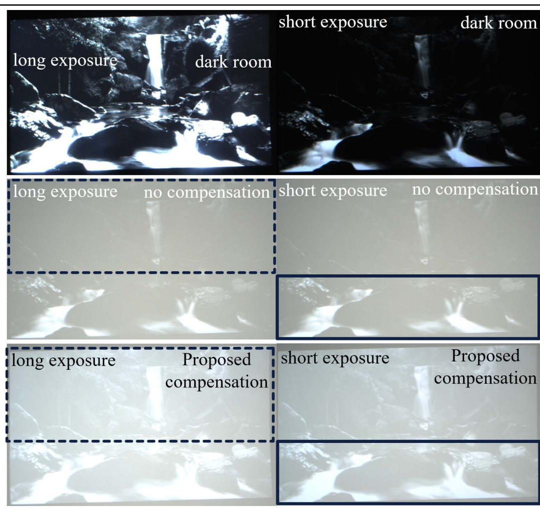

Fig. 7. Captured images, from top to bottom: original image at $A_L = 0$ (dark room), $A_L = 8$ without compensation, $A_L = 8$ with compensation. Dotted box indicates LGR, solid box indicates non-LGR.

MINOLTA CS-2000 spectro-radiometer. Ambient light is implemented using an adjustable LED lamp. A PointGrey BlackFly® vision camera is used as a substitute for eye in order to capture the visibility quality of a virtual image. To emulate ambient light with a fixed intensity, we make the LED lamp light directly incident to the OST-HMD by placing the lamp in front of it as shown in Fig. 6. Then, the intensity of the lamp is dynamically controlled to simulate various ambient light levels. The LED lamp we used is a matrix of equally spaced, very bright LED modules. As they are equally spaced, the resulting light is non-uniform (intensity is spatially variant). To make the incident light uniform, we installed a light filter in front of the lamp. We displayed gray levels 0 through 255 on the OST-HMD, and varied the ambient light level. Measurements were then taken to obtain the luminance data per ambient light level. The overall setup is shown in Fig. 6.

4.2. Experimental results

Table 1 shows the optimal gamma values found by the proposed method for each test image at varying ambient light levels. The test images are classified into three categories in order to show the overall behavior of the optimal gamma. The category 1 contains images with a low APL, large LGR and abundant details. Its LGR contrast loss typically tends to be larger even under weak ambient light. On the contrary, the category 3 includes images with high APL, a small LGR and medium details. Its LGR contrast loss is relatively small as expected. This makes a difference in the optimal trade-off point of the proposed cost function, resulting in higher gamma for high APL images and lower gamma for low APL images. Finally, the category 2 has images with medium APL, a large LGR and little detail. It exhibits little contrast loss, and the optimal gamma tends to be larger than category 1.

Figure 7 shows actual captures of the OST-HMD display seen by the eye-camera. It shows both long and short exposure images side by side. Unlike human eyes, a camera is not able to capture a scene having both very dark and bright regions simultaneously. Therefore, for proper and effortless image comparison, we took two differently exposed images, focused on LGR and non-LGR, respectively. Enhanced contrast is confirmed in the dotted box (LGR) of the long exposure image. Reduced contrast loss is confirmed in the solid box (non-LGR) of the short exposure image. We direct the readers to kindly refer to supplementary materials for other images.

5. CONCLUSION & FUTURE WORKS

In this paper, we took notice of the contrast loss phenomenon and analyzed its cause on OST displays, which is different from that of LCD backlight dimming. We establish a model of this contrast loss phenomenon that can simulate the contrast loss image, based on the model of user-perceived luminance. This contrast loss simulation is utilized for a cost function, which finds an optimal gamma value that compensates the contrast loss of OST displays at LGR. Experimental results confirm that indeed an adaptive gamma tone mapping, which adaptively stretches the LGR, is appropriate to overcome the LGR contrast loss induced by ambient light.

The proposed visibility enhancement applies gamma tone mapping globally to the whole image. This may make a high gray-level region to be saturated, depending on the input image. Therefore, in future studies, the saturating behavior of high gray-level regions should be considered simultaneously in addition to enhancing the contrast of LGR.

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