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Ambient-Light-Adaptive Image Quality Enhancement for Full-Color E-Paper Displays Using Saturation-Based Tone-Mapping Method

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Abstract
For full-color e-paper displays that have a small color gamut, we improve distorted image tones in high-saturation regions using saturation-based tone-mapping curves derived from measured chroma-saturation characteristic. The improvements are experimentally verified via several test charts and natural images. More important, the method can adapt to varying ambient light.

Author Keywords
Electrophoretic display; full-color e-paper display; tone-mapping

1. Introduction
Recent years, reflective displays, represented by electrophoretic displays (EPDs), have been used for lots of applications, such as e-readers, digital signage, and electronic shelf labels, due to their ultra-low power consumption introduced by the bistability, excellent sunlight readability, potential flexibility, etc. [1-3]. In addition to that monochromic EPDs achieve a great success on the e-reader market, a number of studies have been dedicated to full-color EPDs to expand the scope of applications [2-4]. At present, technologies including adding a color filter array, using color particles, or color dye can realize full-color EPDs. Among these technologies, adding color filters can directly use the manufacturing process of conventional liquid crystal displays (LCDs), thus it is the most convenient way to develop practical full-color EPDs [2-4].

However, current full-color EPD technologies cannot achieve a satisfactory color gamut compared with conventional LCDs. For example, while using color filters, the reflective wavelengths of a EPD is highly limited; thus, the spectral bands of the color filters would be sacrificed for a reasonable reflectivity, degrading the color rendering performance. The color gamut of current color-filter-based full-color EPDs is usually no more than 15% NTSC [2-3], as shown in Fig. 1(a). Even color particles or color dyes are adopted; the color gamut is still difficult to exceed 20% NTSC [2-3]. Due to the poor color gamut, while an image with a conventional sRGB gamut is input onto an EPD, the colors that exceed the native gamut of the EPD may give rise to color rendering artifacts. For instance, Fig. 1(b) shows a ground truth image containing red colors with gradient saturations. When it is shown on a 32-inch full-color EPD using color filters, some clipping-like artifacts appear in the regions that have relatively high saturation, which reduces the detail continuity of the original image, as also shown in Fig. 1(b). Therefore, to preserve the continuity and tone of an original image for insufficient color gamut EPDs, an image enhancement method is required. In addition, considering the color rendering performance of an EPD varying with the ambient light, such an image enhancement method should adapt to different ambient light.

Facing the particular issue of EPDs that high-saturation regions tend to be clipped and the original image tone is distorted, we study a 32-inch color-filter type EPD. First, different saturations and brightness in the device-dependent HSB color space are input into the display. Next, corresponding chroma in the CIEL*a*b* color space, which is a device-independent metric associated with perceptual colorfulness, are measured under a specific ambient lighting using a colorimeter. The measurement results show that the perceptual colorfulness is clipped or even declines when the input saturation is higher than a certain value (approximately 80%). Therefore, it is demonstrated that such an abnormal variation of colorfulness with respect to input saturations causes the above-mentioned issue of image tone distortion. To solve this issue, the measured chroma-saturation characteristic is utilized to implement a tone-mapping algorithm by mapping the distorted high saturations into the range that the display can render while maintaining the moderate and low saturations. Experimental results clearly demonstrate the enhancement in high-saturation regions for different test charts and natural images. In addition, the implementation of the proposed method for varying ambient lightings is discussed to make the proposed tone-mapping method more significant for reflective displays.

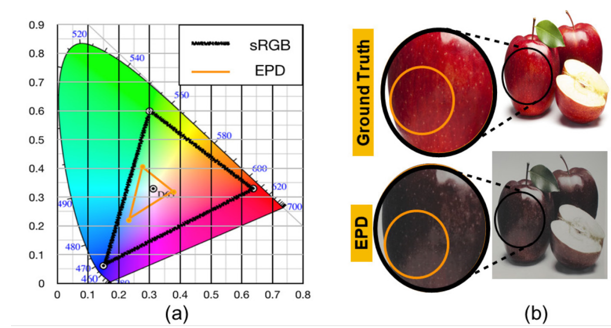

Figure 1. (a) Typical color gamut of a color-filter-based EPD (15.43% NTSC); (b) distorted high-saturation regions on a 32-inch EPD captured by a camera, compared with the ground truth.

2. Enhancement Method

2.1 Concept
To solve the above mentioned problem of image tone distortion in high-saturation regions, the concept of mapping a high dynamic range (HDR) scene to a low dynamic range (LDR) display will be used [5]; i.e., a saturation-based tone-mapping method will map a high saturation range of an input image to a low saturation range of an EPD. To this end, three steps are proposed. (i) Use the device-dependent HSB color space for input images and measure the relationship between device-independent perceptual colorfulness and input S, for different values of H and B. (ii) Find the clipping point, which is an S value beyond which the perceptual colorfulness does not increase or even declines with the increase of S. (iii) Map, or to say effectively compress the S values beyond the clipping

point using a tone-mapping curve, to make all the original S within the range that the display is able to render.

2.2 Measurements

This study adopted a 32-inch color-filter-based EPD with a resolution of 2560 by 1440 and 4-bit grayscale from E Ink Holdings. To measure its color performance, the display is placed in a light box (model: SpectraLight QC from X-Rite), and a colorimeter (model: SR-UL1R from TOPCON) aiming the displays' center is placed 0.5 m away. Figure 2 shows the measurement apparatus. Also, a Nikon D750 with a 35mm-lens replace the colorimeter to capture an image displaying on the EPD.

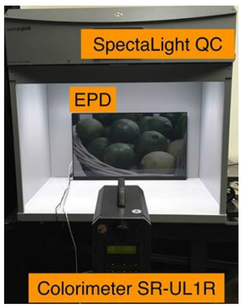

Figure 2. Measurement setup including a color EPD in a light box and a colorimeter.

To quantify the perceptual colorfulness, the device-independent CIEL*a*b* color space is adopted for the measurements, and chroma C^*_{ab} derived in this color space, as $C^*_{ab}=\sqrt{a^{*2}+b^{*2}}$, is used. Here, a larger C^*_{ab} denotes a more chromatic color under a certain brightness. On the other hand, the device-dependent HSB color space is used to represent the color information in an input image, where HSB and sRGB values can be easily interconverted [6]. In the following discussion, H, S, and B will stand for the components in the HSB color space.

The relationship between the device-independent C^*_{ab} and the device-dependent S needs to be comprehensively measured. Therefore, S from 0.1 to 1 with an interval of 0.1 (0.1, 0.2, 0.3…1) is considered for 10 measurements. In view of the 4-bit grayscale, B is divided into 16 steps (0, 1, 2…15). Moreover, measurements are carried out for three primary colors: red (H = 0º), green, (H = 120º), and blue (H = 240º). In this way, 480 different combinations of HSB values, as 10 steps of S, by 16 steps of B, by three steps of H, are adopted. The 480 HSB values are then converted to sRGB values and shown on the EPD.

The illuminant is first set to D65, and the illuminance on the display is 1240 lux. Next, using the colorimeter to obtain CIE tristimulus values (XYZ) of the test patterns and converting them to CIEL*a*b* values using D65 as the white point, chroma C^*_{ab} of the test patterns are obtained. Figure 3 shows the variation of C^*_{ab} with respect to S for different values of B. As can be seen from Fig. 3, chroma C^*_{ab} starts to be clipped or even declined when S is larger than a certain value, meaning that the perceptual colorfulness produced by S larger this value is not higher than that produced by smaller S. To verify such an abnormal phenomenon, a test bar containing S varying from 0.1 to 1 (B = 12, H = 0º) is displayed on the EPD and captured, as also shown in Fig. 3, where the right side of the bar, corresponding to large S, appears less chromatic abnormally. For comparison, ideal variations of chroma and perceptual colorfulness with respect to S are shown at the bottom of Fig. 3, to demonstrate how this bar appears on an ideal display. Here we define "clipping points" for red, green, and blue colors, which are values of S beyond which chroma C^*_{ab} starts to be clipped or declined, denoted as S_{thR}, S_{thG} and S_{thB}, respectively. Note that, for a certain primary color, the variations of C^*_{ab} with respect to S are not identical for different values of B, implying that different clipping points can be determined for different values of B. Nevertheless, in the following tone-mapping method, a clipping point varying with B means that different extents of modification will be applied to contents with different brightness, which may cause visible contour artifacts for the EPD with only 4-bit grayscale. Therefore, a single clipping point should be set for a certain primary color by finding out the common characteristic among the chroma-saturation curves for different values of B. Finally, from Figs. 3(a) to (c), S_{thR}, S_{thG} and S_{thB} are determined to be 0.8, 0.8, and 0.75, respectively.

2.3 Saturation-Based Tone-Mapping

From the measurement results, an abnormal phenomenon is found that the perceptual colorfulness under a certain brightness, quantified by C^*_{ab}, does not increase with the increase of S when S is beyond a certain clipping point. Therefore, as mentioned in Section 2.1, we need to map saturation information beyond the clipping point, which exceeds the EPD's rendering ability, to the range within this point, as called a saturation-based tone-mapping method. For a certain primary color (red, green, or blue), the tone-mapping method is here explained in details with the aid

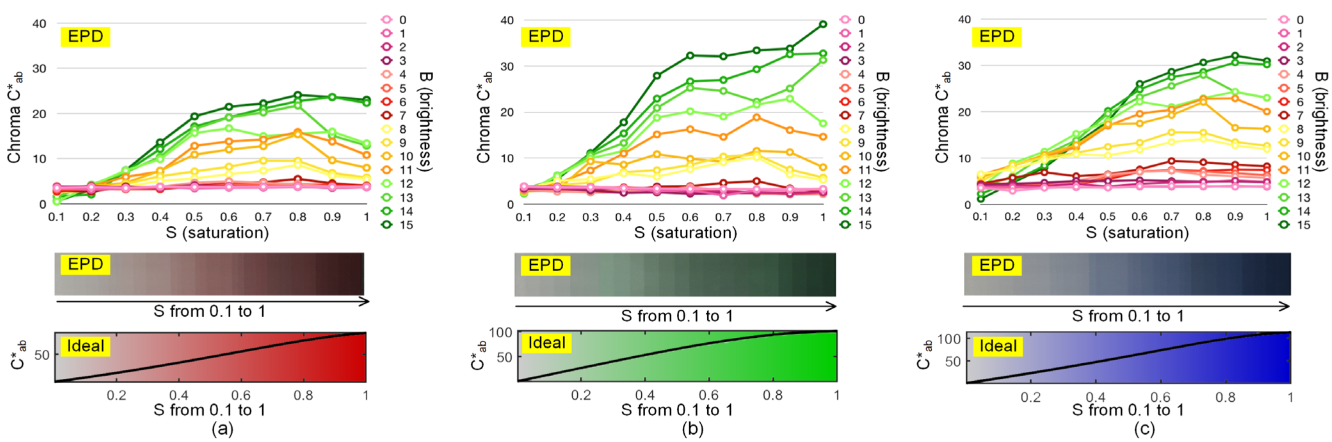

Figure 3. Upper: Chroma C^*_{ab} varying with S (saturation), corresponding to different values of B (brightness). Middle: EPD-displaying and camera-capturing test bars containing gradient S with B = 12. Lower: ideal test bars also containing gradient S with B = 12, for the variations of chroma and perceptual colorfulness. (a) red (H = 0°); (b) green (H = 120°); (c) blue (H = 240°).

of the illustration in Fig. 4. First, using the quasi gamma curve described by Eq. (1), original saturations distributed from 0 to 1 are mapped into the range of 0 to S_{thX} (X denotes R, G, or B, as the clipping points obtained before). Next, to correctly reproduce the color information in the ground truth image, moderate and low saturations should be maintained; hence, the intersection between the quasi gamma curve and "S' = S" is found, and original saturations on the left of this intersection are maintained. In this way, only the tones of high saturations that are on the right of the intersection, including those are originally clipped, are compressed. By considering that a high dynamic range of saturation in the ground truth is displayed on a device with a low range, namely the EPD, such a cost of tone compression for high-saturation contents is necessary; i.e., preferable to tone clipping. Figs. 4(a) to (c) show the tone-mapping curves for the three primary colors by setting γ_X to 0.45. In fact, the quasi gamma curves on the right of the intersections are very close to straight lines, and little affected by the value of γ_X.

$$S' = S_{thX} \cdot S^{\gamma_X} \tag{1}$$

where γ_X is used to modify the shapes of the quasi gamma curves.

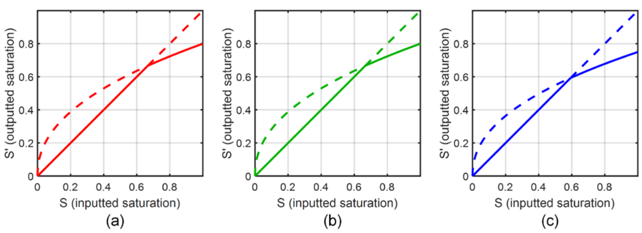

Figure 4. Tone-mapping curves (solid lines) for: (a) red (H = 0°); (b) green (H = 120°); (c) blue (H = 240°), where the dashed lines denote the auxiliary quasi gamma curves and "S' = S."

In addition, for a pixel in a ground truth image whose H (hue) component does not coincide with red, green, or blue, its saturation-based tone-mapping curve is obtained via an simple interpolation between the curves of its two adjacent primary colors, as given by Eq. (2).

$$S' = \frac{\Delta H_1}{120^\circ} \cdot f_1(S) + \frac{\Delta H_2}{120^\circ} \cdot f_2(S) \tag{2}$$

where ΔH_1 and ΔH_2 and hue difference (in degree) between the pixel's H component and its two adjacent primary colors, which have tone-mapping curves of $f_1(S)$ and $f_2(S)$, respectively.

3. Experiments and Results

To verify the effectiveness of the proposed saturation-based tone-mapping method, in this section, some test charts and natural images are processed and displayed. In specific, for an image to be displayed on the EPD under the D65 illuminant, it needs to be first converted to HSB color space. Next, values of S are mapped to new values using the tone-mapping curves in the previous section. Finally, the new HSB values are converted back to sRGB ones and input into the EPD.

First, the before-used test bars containing gradient S with a constant value of B of 12 are adopted. In Fig. 3, the clipping or decline of perceptual colorfulness for high saturations causes the right side of the bars to appear less chromatic. Now they are processed by the proposed method and displayed on the EPD under the D65 illuminant. Figure 5 simultaneously compares the unprocessed and processed images captured by the camera. It can be seen that the right side of the bars become more chromatic after processing, revealing that the proposed method solves the problem of clipped or declining perceptual colorfulness beyond the clipping points. Nevertheless, the changing rates of perceptual colorfulness in the right side are a little smaller than that in the left parts, indicating that a tone compression takes place in the high-saturation regions after the processing. As discussed before, this is a necessary cost for the EPD with an insufficient color gamut.

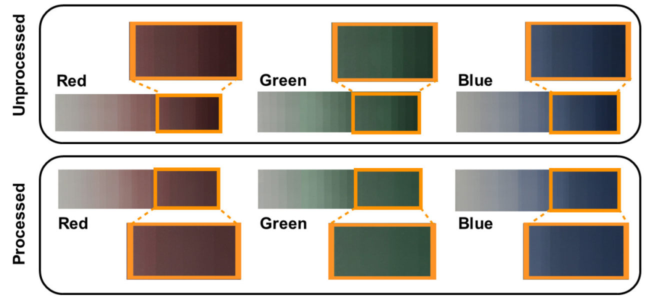

Figure 5. Captured images of unprocessed and processed test bars containing gradient S with B = 12, where the clipped or declining perceptual colorfulness in high-saturations regions (enlarged) is improved.

Next, several natural images are adopted to further verify the proposed method. Figure 6 shows the enhancement result of the image that was used to demonstrate the problem of image tone distortion in Section 1, and the region where the proposed method takes effect is enlarged. As can be seen, the image tones in high-saturation regions on the apple are recovered after processing; that is, the image tones in the ground truth are reproduced more correctly. Two landscape images (LAKE and SKY) are also adopted for verification, as shown in Fig. 7, where the recovered image tones in high-saturation regions (lake and sky) are highlighted and demonstrated clearly. In addition, the significant contour artifacts in SKY that are caused by the EPD's low color rendering capacity are also improved by mapping the high saturations into the EPD's color rendering capacity.

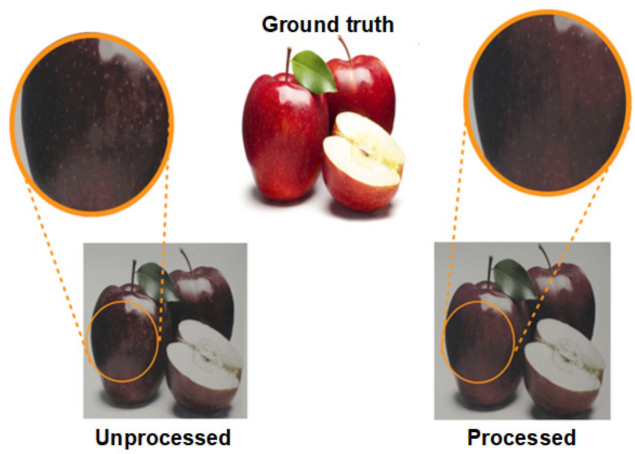

Figure 6. Natural images unprocessed (left) and processed (right) by the proposed method, as well as the ground truth. The recovered high-saturation regions are enlarged.

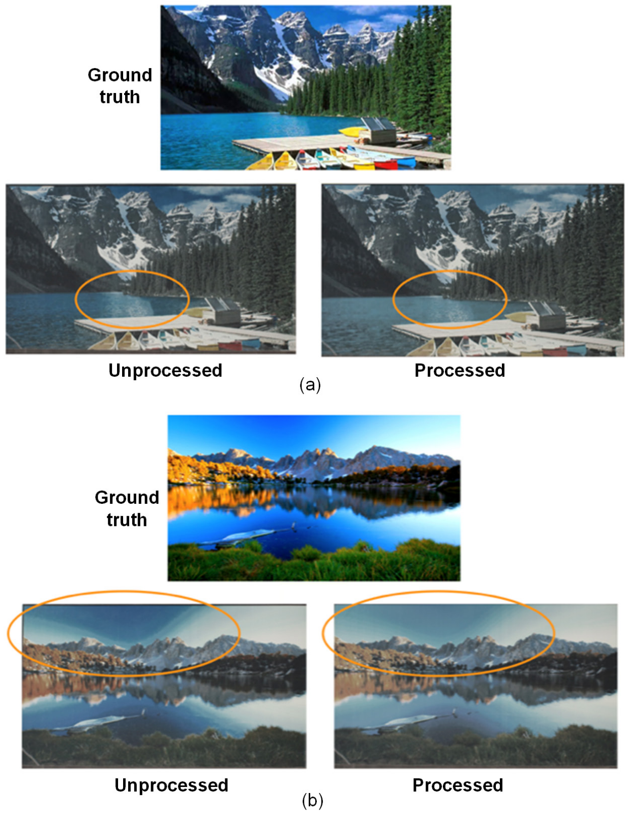

Figure 7. Natural images unprocessed (left) and processed (right) by the proposed method, as well as the ground truth: (a) LAKE; (b) SKY. The recovered high-saturation regions are highlighted.

4. Discussion for Varying Ambient Light

The measurements, tone-mapping processing, and enhancement results discussed above are all for a D65 illuminant, while varying ambient light must be considered for reflective EPDs. In fact, the proposed method is fully ambient-light-adaptive via re-obtaining the chroma-saturation characteristic for an unknown ambient lighting, as illustrated in Fig. 8. Of the procedures in Fig. 8, the key step is to obtain the display's device-independent color performance through a single-shot camera. In specific, the display first presents a test matrix containing different combinations of H, S, and B, as shown in the first block in Fig. 8. Next, a single-shot camera takes a photo of the matrix, and the RGB values in the photo can be used to calculate the CIE tristimulus values (XYZ) of all the units in the matrix, which can be accomplished by a well-established camera-based colorimetric characterization [6], as long as the camera is accurately calibrated. Having obtained the CIEXYZ data, we can easily derive chroma C^*_{ab} and achieve the chroma-saturation characteristic, as shown in Fig. 3. Through analyzing the data, we can determine new clipping points and corresponding tone-mapping curves. In this way, for an unknown ambient lighting, procedures need to be carried out, only including displaying a beforehand matrix, capturing by a single-shot camera, and doing simple data processing. Therefore, the proposed image enhancement method can be automatically implemented for varying ambient light.

5. Conclusion

Facing a small color gamut of full-color e-paper displays, we sought to solve the problem of image tone distortion in high-saturation regions. By adopting a 32-inch color-filter-based EPD, the relationship between its perceptual colorfulness and the device-dependent color information in input images was comprehensively measured. An abnormal phenomenon that the colorfulness is clipped or even declines beyond certain clipping points was found. According to the clipping points, the original saturations in input images were mapped to the range the EPD is able to render via the saturation-based tone-mapping curves. As a result, the image tones in high-saturations regions were recovered and the image qualities were enhanced by testing several charts and natural images. More important, to obtain tone-mapping curves for an unknown ambient lighting, only a beforehand matrix needs to be re-captured by a single-shot camera, revealing that the proposed method can be easily and automatically implemented for varying ambient light. For full-color e-paper displays that will encounter an insufficient color gamut for a long time, such an ambient-light-adaptive method for enhancing image quality is of great significance.

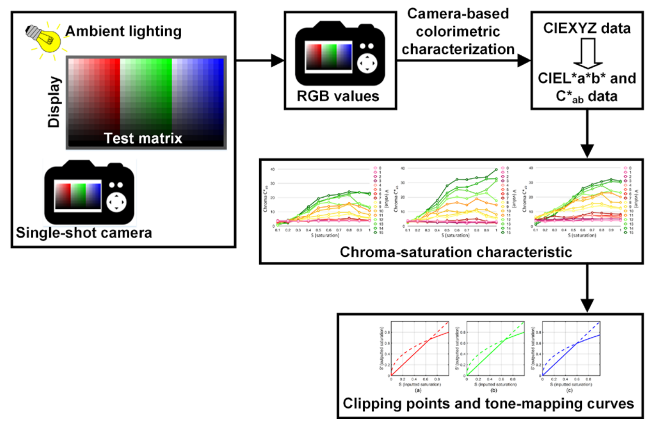

Figure 8. Flow chart of the proposed image quality enhancement method for varying ambient light.

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