Reproducing high dynamic range contents adaptively based on display specifications

Ruidong Zhu[1,2], Abhijit Sarkar[1], Neil Emerton[1], and Tim Large[1]

[1]Microsoft Corporation, Redmond, Washington 98052, United States

[2]College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816

E-mail: ruidong.zhu@knights.ucf.edu, Phone: 407-443-1648; Fax: 407-823-6880

Abstract

We developed a new approach to display HDR contents on both HDR and SDR displays. A 12-bit HDR display is built up to test the algorithm. We have also conducted psychophysical experiments to determine how much dynamic range is needed to make the SDR display resembles the HDR display.

Keywords: high dynamic range, gamut mapping, psychophysical experiment.

A. This paper can be considered for either ORAL or POSTER presentation.

B. This paper is NOT intended for Applications Sessions.

C. Symposium: Applied Vision/Human Factors

D. The main author is currently a student.

1. Objective and Background

We live in a high dynamic range (HDR) world where for natural scenes the luminance range can vary from below 10^{-3} cd/m^2 (nits) for star light to above 10^5 nits for direct sunlight, and the corresponding dynamic range is over 10^8:1 [1]. To faithfully reproduce the real world, the display is required to have both luminance and dynamic range close to the real world. Recently, with the improvement of organic light emitting diode (OLED) displays [2] and local dimming liquid crystal displays (LCD) [3], it is possible to manufacture displays with peak brightness over 1000 nits and dark state below 0.05 nits. These HDR displays can better reproduce the real world.

Content wise, the entertainment industry is busily adapting to HDR for better viewing experience. Compared with traditional standard dynamic range (SDR) contents, these HDR contents are usually color graded beforehand for more vivid colors. At the same time, the peak luminance of these HDR contents are usually mastered to ~1000 nits to accommodate contemporary HDR displays.

While HDR display has great potential, it is still not ready to take over the whole market. For OLED display, the concern is mainly about the cost and white uniformity while for local dimming LCD, LED driving and the overall device size are the most critical challenges. Thus, it will be quite rewarding if we can display HDR content on contemporary SDR displays. In this paper, we have analyzed the challenges in displaying HDR contents and propose a new algorithm based on HDR gamut mapping to display HDR content on both HDR and SDR displays. To test the algorithm, we built up a 12-bit HDR display and displayed the original content and gamut mapped image simultaneously. At the same time, we have conducted a psychophysical experiment to examine how display luminance range will affect the performance of the SDR display.

2. Contemporary display pipeline

In terms of displaying HDR contents, there are three main challenges. The first one is the luminance range, for HDR content, the highlights usually have luminance of ~1000 nits while contemporary SDR display usually has a peak brightness of ~450 nits. The other example is that sky at night are usually intended to be totally dark (0 nits), while contemporary SDR display comes with a dark state of ~0.25 nits. The luminance range problem can happen even for HDR displays as sometimes HDR scenes can go way beyond 10000 nits. The solution to this problem is the tone mapping approach by compressing the luminance range to that of the display. The second problem concerns the color gamut. Professional HDR contents are encoded with BT.2020 color gamut [4] while the majority of contemporary SDR displays can only fulfill sRGB. The problem can be partially mitigated by gamut mapping, which transforms all the colors to within the device color gamut. The final problem relates to the bit-depth, as contemporary 8-bit convention might result in visual banding [1]. And that is why the industry is moving towards a 10-bit solution. Display bit depth is not the subject of this paper.

After analyzing the challenges in displaying HDR content, we would like to discuss a little bit about how HDR content are displayed on contemporary SDR devices.

For an HDR frame, after decoding from YUV to linear RGB [5], the contemporary SDR display transforms linear RGB to absolute XYZ values through Eq. (1):

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = LM \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{1}$$

Here L is the luminance factor equals to the display brightness and M is the color transformation matrix. For a sRGB display,

$$M = \begin{bmatrix} 0.412424 & 0.357579 & 0.180464 \\ 0.212656 & 0.715158 & 0.0721856 \\ 0.0193324 & 0.119193 & 0.950444 \end{bmatrix} \tag{2}$$

With this approach, RGB values smaller or equal to unity are transformed as is, while RGB values larger than unity are clipped to one. In this way, RGB value of (1,1,1) are transformed to display white.

The performance of this approach is demonstrated in Fig. 1(a), this image is from the HDR trailer of *Life of Pi*. Lots of the scene are interpreted as white and it appears that the actor is travelling under direct sunlight. However, as is demonstrated by Fig. 1(b), which is a tone mapped version of the original scene via highlight compression, the real intention of the creator is that the actor is actually travelling at sunset or sunrise. In this sense, contemporary approach in displaying HDR content could mess up the creator's intention.

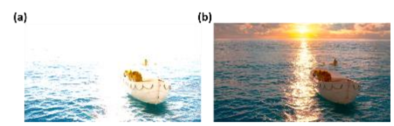

Figure 1. (a) How HDR content are currently displayed on SDR devices, and (b) the real intention of the creator (tone mapped version of the original image)

The reason that contemporary display principle doesn't work is that for HDR content, the linear RGB values can go beyond unity and at the same time, they come with absolute luminance info [5]. For example, for Fig. 1, this clip has a luminance factor L of 80 and reference white is actually 80 nits. In this way, the grayish clouds area (with RGB values around 2) is actually ~160nits while contemporary display "interpret" that they are beyond display white and clipped them to display white.

3. Displaying HDR content through HDR gamut mapping

As is mentioned above, contemporary display pipeline cannot faithfully reproduce HDR content. To solve this problem, we have developed a new approach to display HDR content. In contemporary TV, after decoding the content to RGB values, the contents are first gamut mapped and then tone mapped before finally being displayed on HDR/SDR display [6], as is demonstrated in Fig. 2(a). During our research, we propose the HDR gamut mapping approach to solve the luminance problem and the color gamut problem simultaneously, as is illustrated in Fig. 2(b).

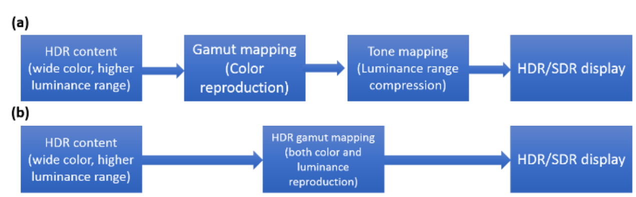

Figure 2. (a) Display pipeline for HDR contents on contemporary TV and (b) the proposed HDR gamut mapping algorithm.

In detail, the HDR gamut mapping approach has the following steps:

1) Determine the reference white. The reference white we select has absolute XYZ value of (76.0374, 80.0000, 87.1176). This white point is selected based on the content metadata, sRGB standard and the fact that most displays have D65 white point.
2) Select the working color space. Here we select the IPT color space [1] because of its simplicity and hue linearity. The IPT color space is also extended to beyond unity to allow for RGB values larger than one.
3) Construct the color gamut of an ideal wide color gamut HDR display. Here we assume the original display is an HDR display with a peak brightness of 1200 nits and is fully capable of Rec. 2020. All the colors it can reproduce is converted to the IPT color space.
4) Construct the color gamut of the real SDR display. The target display here is with peak brightness of 400 nits and sRGB color gamut. Similarly, all the colors it can reproduce is converted to the extended IPT color space.
5) Gamut mapping from the original color gamut to the destination color gamut. The approach we use here is the Chroma-dependent sigmoidal lightness mapping and cusp knee scaling (SGCK) [7]. Of course, other gamut mapping approach can also be used.

The color gamut of both the HDR and the SDR display is demonstrated in Fig 3(a) and the working principle of the HDR gamut mapping approach is depicted in Fig. 3(b). Basically this approach scales lightness and chroma on a constant hue plane. The advantages of this approach are twofold: 1) This approach is a color-by-color reproduction; thus, it is relatively easy to incorporate it into the hardware level as a 3D look up table (LUT); 2) This approach is display adaptive. For example, if the peak brightness of the SDR display is 600 nits, we just need to do the gamut mapping again and create another 3D LUT.

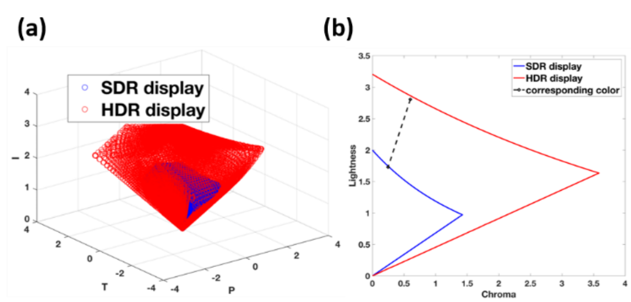

Figure 3. (a) the color gamut of both the HDR display and the SDR display and (b) the principle of the HDR gamut mapping approach.

4. Hardware setup and psychophysical experiments

To test the algorithm, we built up an HDR display by combining a projector with an LC module [2]. The specifications of the HDR display is listed in Table 1. With this HDR display it is possible to both display HDR contents and simulate an SDR display.

Table 1. Specifications of the HDR display.

Peak brightness	1160 nits
Dark State	0.002 nits
Contrast Ratio	580,000:1
Color gamut	sRGB
Bit depth	12 bit

Besides testing the algorithm, another reason we would like to set up this device is that even though contemporary SDR displays are still inferior to the HDR displays, it is possible to improve their performance to some extent. Thus we would like to know how peak brightness and dark level will affect the performance of SDR display. For these two purposes, we conducted a psychophysical experiment. The experiment was conducted as follows:

We prepared eight HDR images and these images are listed in Fig. 4. Except for the second image, all the other HDR contents are from the HDR clip *Colors of the Journey* and the images are tone mapped versions of the original HDR frames via highlight compression. For each HDR image, ten versions were created: The first version was a gamut-mapped version from BT. 2020 to sRGB to accommodate the HDR display's color gamut, this version was still HDR. For the other nine versions, they were the SDR versions that had been processed with the HDR gamut mapping. The difference between these images were that they came with three different peak brightness settings: 400 nits, 640 nits and 800 nits. As for the dark level, there were also three configurations:0.005 nits, 0.1 nits and 0.25 nits. Thus there were 10 versions in total. The psychophysical experiment was conducted through pair comparison. A random version from the SDR images was displayed together with the HDR image, and the viewers were asked to judge how similar these two images were based on five categories: 1) overall brightness 2) details 3) colors 4) highlights and 5) dark shadows. Then they gave a score between 0% (totally different) to 100% (identical) to describe the similarity between the two images. The viewing condition was dark with ambient illuminance of 10 lux.

Figure 4. The eight HDR frames used in the test

This process is demonstrated in Fig. 5. The top image is an SDR version with peak brightness of 400 nits and dark level of 0.25 nits while the bottom image is the HDR version. Fig. 5 is taken directly from the HDR display with an iPhone 7 and because of the camera limit, it is not identical to what the viewers saw on the display. Still we can tell that the HDR version has brighter highlights and better color saturation than the SDR version. However, comparing Fig. 5 with Fig. 1 we can tell that our HDR gamut mapping approach can well reproduce the HDR content.

Figure 5. Comparing the SDR image with the HDR version

After all 18 viewers gave their answers for all of the images, we analyzed the data and find some important results. The first question we would like to ask is: "black or white: which is more important?" The reason we ask this question is that for the two mainstream display technologies, they have different challenges when dealing with HDR contents. For OLED the dark level can be perfectly black, however because of the lifetime issue it is not recommended to make the peak luminance too bright. On the contrary, for LCD the peak brightness can be extremely high by using high power LED, whereas the dark state is usually not satisfying because of the light leakage. The first conclusion is that dark level is as important as peak brightness. This can be seen from the results for Fig. 4, image (2) and (3), which is listed in Table 2. For image 2 the average luminance of the scene is 220 nits and the sun area is over 1000 nits. When we increase the peak brightness the perceived similarity between the SDR and the HDR image dramatically increased. Whereas when we decrease the dark level, the similarity didn't improve much. In fact, if we calculate the correlation coefficient r_b between dark level and similarity score, the result is r_b=-0.159, which indicates poor correlation. Whereas for the relationship between peak brightness and similarity score, the correlation coefficient r_w=0.954. This indicates that for image (2), people care much more about the white level than the dark level. As for image (3), the average luminance is only 0.38 nits and the night sky is intended to be pitch black. This time in general decreasing the black level has greatly improved the similarity score (r_b=-0.886), whereas the peak brightness is poorly correlated with the image similarity with r_w=-0.024. This indicates for this image, even though the stars should be over 1000 nits, people are way more sensitive to the black level because it is a night scene. Summarizing these results together, we can see the influence of peak brightness and dark level is image dependent and to cater to all the different image types, the dark level and peak brightness should be improved simultaneously.

Table 2. Similarity (in percentage) for Fig 6, image (2) (data on the left side) and (3) (data on the right side).

b\w	400	640	800
0.005	55	61.31	68.13
0.1	56.25	61.44	63.63
0.25	52.19	61.19	65.31

b\w	400	640	800
0.005	67.81	72.63	70.19
0.1	70.88	70.31	69.63
0.25	60.63	60.81	57.88

When we average the scores for all these images, we get Table 3, from it we can see that for the worst scenario, viewers still give a high similarity score of 68.82%, which indicates our HDR gamut mapping approach works quite well. A closer look at the data demonstrates that in general higher peak brightness and darker black level improves the similarity. However, at 0.1 nits to 640 nits, people give a high similarity score of 75.05%, and the improvement after that isn't that dramatic. This indicates such dynamic range can be a good spec for SDR display to make them look like HDR display. When we draw black level and peak brightness independently. We get Fig. (6), which also indicates 0.1 nits to 640 nits can be a good specification for luminance range requirement of the SDR display.

Table 3. Similarity scores (in percentage) on average.

b\w	400	640	800
0.005	**71.92**	**75.92**	**76.70**
0.1	**72.41**	**75.05**	**76.98**
0.25	**68.82**	**73.98**	**75.5**

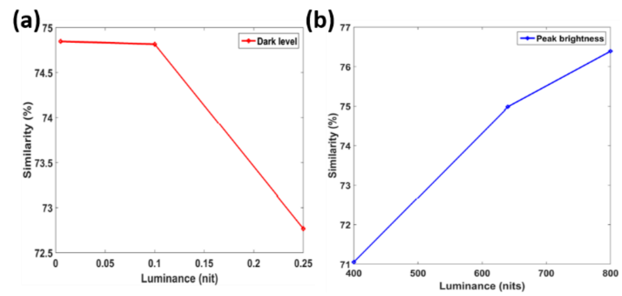

Figure 5. How similarity varies with (a) dark level and (b) peak brightness.

5. Impact

With our proposed HDR gamut mapping approach, it is possible to faithfully reproduce HDR content on SDR display. At the same time, this display adaptive color-by-color reproduction can be incorporated into low level hardware as a 3D LUT. The algorithm is validated through hardware implementation and psychophysical experiment. The psychophysical experiment also indicates that with luminance range between 0.1 to 640 nits, it is possible to make the SDR display resembles an HDR display.

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