國立交通大學

顯示科技研究所

碩士論文

彩色背光演算法應用於
高動態範圍液晶顯示系統

Color Backlight Algorithms on
High Dynamic Range Liquid Crystal Display Systems

研究生：王國振

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碩士論文

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摘　要

低功率與高畫質的顯示器，近年來已成為顯示器研發的主要趨勢。由於傳統顯示器設計，受限於背光系統與液晶之組合，無法有效降低暗態，進而影響其顯示對比之能力。因此最早是利用影像處理方法，解決在受限的顯示器上呈現高動態範圍的影像，現今業界已經研發出可呈現高動態範圍的顯示器，但其影像顯示品質與功率消耗表現仍未臻完善。本論文提出以現今高動態範圍顯示器的技術為基礎，進而使用分區調整三原色(紅色、藍色、綠色)的背光，使現有高動態顯示器的暗態能進一步被優化，讓顯示器能達到更好的對比能力，除此之外，此技術更能減少漏光的效應，使其達到更高的色彩飽和度，最終還能達到更節省功率消耗且維持住影像細節的目的。

由實驗結果可證明，此方法已成功的應用在 37 吋高動態範圍液晶顯示器，使其在高對比的影像對比度從 20,000:1 提升至 40,000:1 且畫面細節能被維持住，並有效的使色域從 108% NTSC 擴展到 125% NTSC，且相對於傳統的液晶顯示器能降低 50%的背光損耗。

Color Backlight Algorithms on High Dynamic Range Liquid Crystal Display Systems

Student: Guo-Zhen Wang
Advisor: Dr. Han-Ping D. Shieh, Prof. Yi-Pai Huang

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Abstract

Low power and high image quality have become the major trend of display research in recent years. The contrast ratio of conventional liquid crystal display is limited to the full-on backlight system. Traditionally, the solution is to perform image processing in the low dynamic range display. High dynamic range displays were proposed by adopting the local dimming LED backlight system. Although, it can display high contrast images, but can not optimize power consumption and image quality. In this thesis, we proposed the two color backlight algorithms, DCA and SCC, by controlling *R, G, and B LEDs* individually to optimize the traditional high dynamic range displays. This method could improve the contrast ratio by reducing dark state and enhance color saturation by reducing the effect of light leakage. Besides, it could reduce more power consumption and keep image details.

This method has been demonstrated that color backlight algorithm implemented on a 37" high dynamic range liquid crystal display (HDR-LCD) TV can yield contrast ratio of ~40,000:1 with clear image details. Furthermore, the color gamut can be enlarged to 125% of NTSC and reduced 50% power consumption compared to full-on backlight.

Acknowledgment

I am especially appreciated to my advisor- Professor Han-Ping David Shieh, who gave me valuable advices and prolific resources in my two-year graduate life. Therefore, I have improved my ability to finish the thesis. Besides, I am grateful for Professor Yi-Pai Huang, who gave me a lot of valuable feedbacks and many useful suggestions when I encountered difficulties in my research.

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Finally, I owe a great deal to my parents and my girlfriend for their support during these days. I will remember every day in this lab. In the future I will use my ability to help everyone who needs to help.

Guo-Zhen Wang in June,2008

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Chapter 1

Introduction

Image quality and power consumption have become major issues for commercial monitors/TVs. However, a drawback of conventional LCDs is low contrast ratio (CR) (about 1,000:1) due to the light leakage of liquid crystals and non-perfect polarizers. After dynamic-backlight-controlled technologies proposed, the image dynamic range of LCDs could be improved [1][2][3][4].Therefore, a suitable backlight algorithm has become an important part in high dynamic range (HDR) systems.

1.1 Motivation and Objective

In the recent years, the issues of limited dynamic range of displays have been extensively studied. The dynamic range we perceive in the real world (14 orders) is approximately eleven orders larger than that of display devices (3 orders) as shown in Fig. 1-1. Therefore, the conventional displays can not present all information of the real world. As the display technologies were improved, high dynamic range displays can be reached by enhancing bright state and decreasing dark state of images. From energy-saving viewpoints, it will cause more power consumption by using high power LEDs to enhance bright state. Thus, various dynamic-backlight controlled technologies were proposed to reduce power consumption and decrease dark state of images.

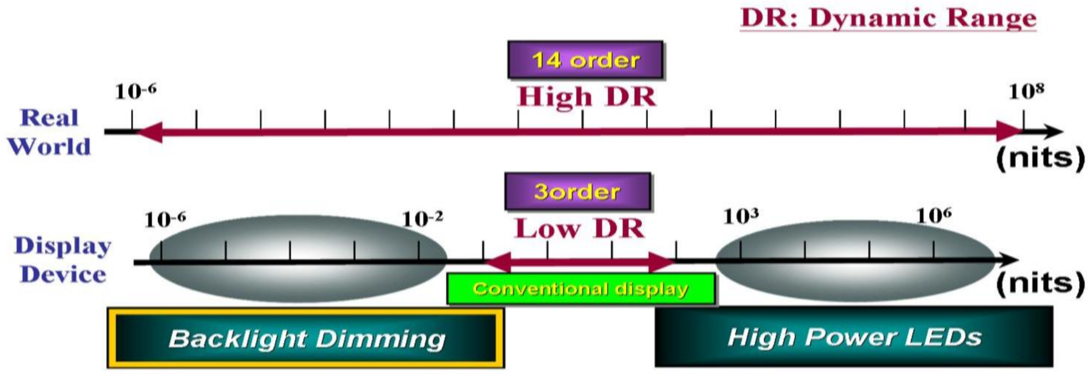


Fig. 1-1 Dynamic range of real world and conventional display device.

Backlight system is important for displays. Currently, cold cathode fluorescent lamps (CCFLs) are the most popular backlight sources for LCDs. However, the CCFLs are not suitable for local dimming. Therefore, Hg-free LEDs are widely used in recent years.

Backlight dimming technologies of different dimensions are compared in Fig. 1-2. 0D backlight dimming dims all backlight, 1D backlight dimming dims line by line, and 2D backlight dimming is locally dimming. The luminance distribution of backlight becomes more similar to the original image when increasing the dimming dimension. Therefore, LED backlight system is one of the best options for 2D backlight dimming technologies. 2D dimming can have lower luminance in the dark state of images by controlling the local brightness independently. In this thesis, 2D dimming technologies will be called “Intensity Control” due to controlling equally three dimensions of backlight (R, G, and B). However, the traditional backlight dimming technologies did not consider three dimensions of image information (R, G, and B) independently.

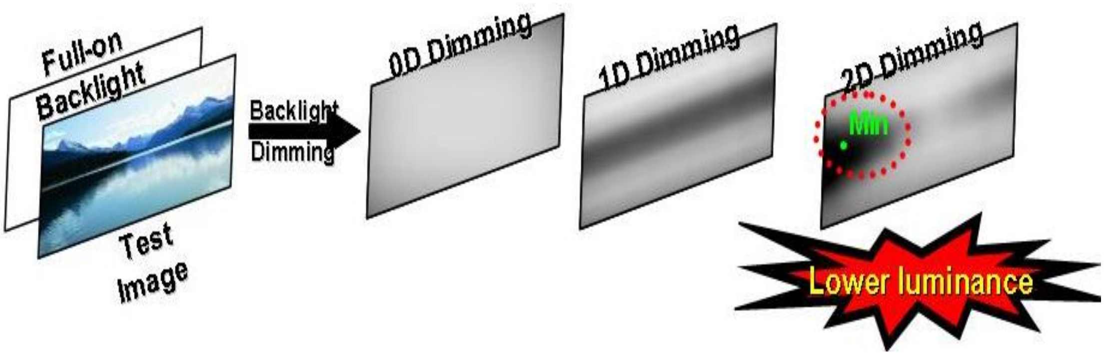


Fig. 1-2 Comparison of different backlight dimming technologies.

In comparison with conventional high dynamic range liquid crystal displays (HDR-LCDs) with intensity control, there are some advantages in HDR-LCDs with color control, as shown in Fig. 1-3. The region within the dot circle of the target image has more red information. The traditional intensity backlight control can only get Black/White (B/W) gray backlight signals without considering three dimensions of image contents. Therefore, the traditional method will waste much power consumption. Besides, the B/W gray backlights will result in some light leakage due to LC structure and color filters. Consequently, color backlight control is proposed to reduce power consumption and enlarge the color gamut due to less light leakage.

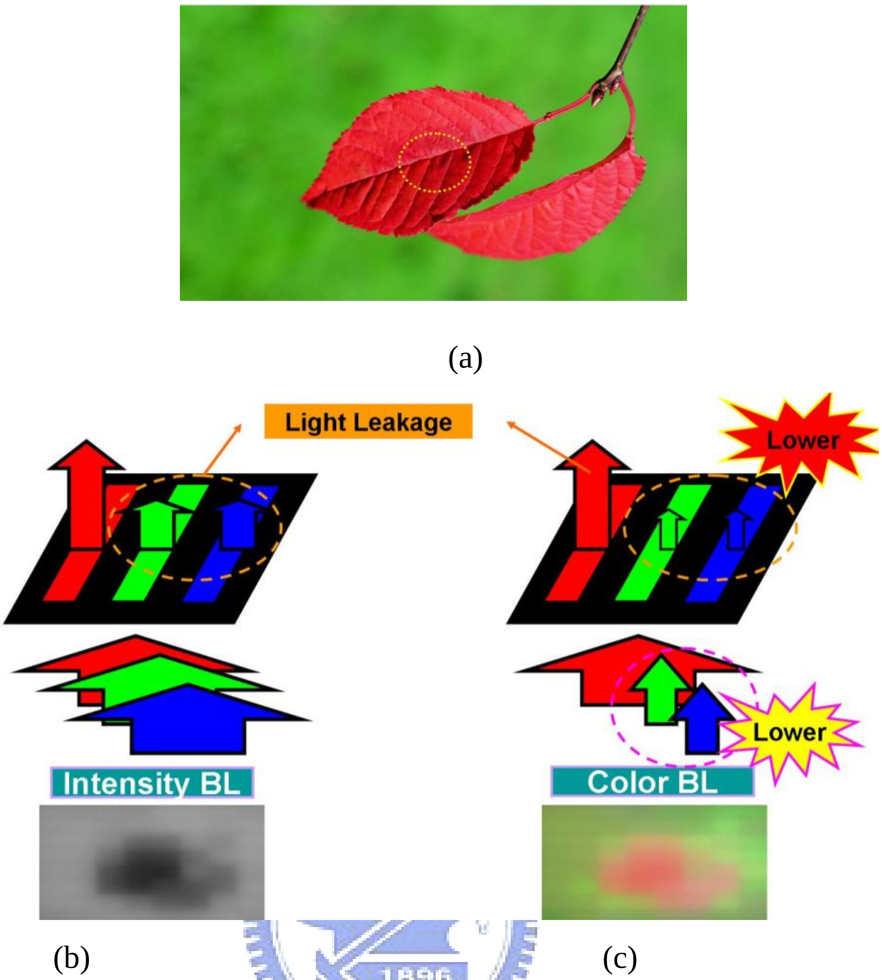


Fig. 1-3 (a) The target image, (b) intensity backlight control, and (c) color backlight control

The LED backlight unit of a 37" LCD was divided into 8×8 zones to reduce the computational complexity of hardware in our experiments. The objective of this thesis research is to enhance the dynamic range of the HDR-LCD to above 30,000:1 in high contrast images; to enlarge the maximum color gamut of the HDR-LCD to 120% of NTSC; and to reduce the power consumption by approximately about 40% by developing optimized color backlight algorithms.

1.2 Dual-Panel Display with Color Backlight Algorithm

The HDR-LCD system is studied as a dual-panel display for enhancing the image quality. One is LED backlight which can control RGB LEDs individually. The other one is LC panel with high resolution to compensate image details (as show in Fig. 1-4). Backlight panel is a low resolution panel for controlling the contrast ratio of images. In this thesis, we propose two novel color backlight modulation algorithms, the Delta-Color Adjustment (DCA) method and the Segment Color Control (SCC) method to optimize the backlight image according to the three dimensions of information of each frame. The color backlight algorithm can not only keep high contrast ratio but also reduce more power consumption. For the LC panel, it is a high resolution panel for compensating the image details, LC signals is adapted according to three dimensions of backlight distribution signals. Finally, the dual-panel display with color backlight algorithm could reach high color saturation, low power consumption, and high contrast ratio by the LED backlight (low resolution), and preserve image details by the LC panel (high resolution).

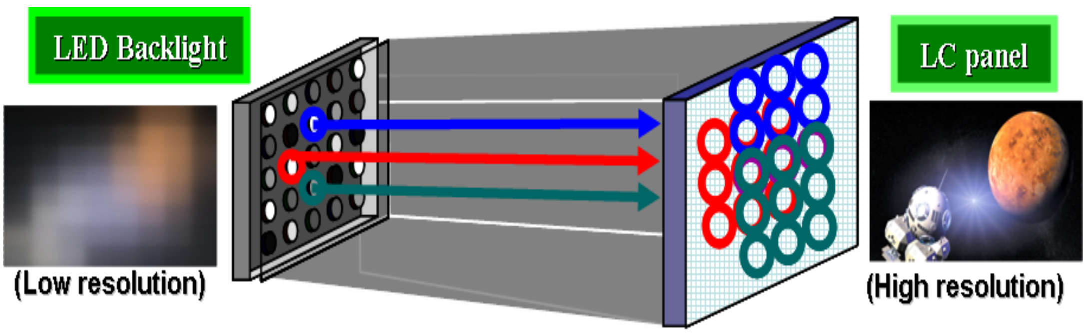


Fig. 1-4 Dual-panel system

1.3 Organization of This Thesis

The objective of this thesis is to develop optimized algorithm for backlight module to improve the contrast ratio, keep image details, higher color saturation and lower power consumption on the current dual-panel display system. This thesis is organized as follows: The prior arts of high dynamic range display are presented in **Chapter 2**. The proposed color backlight algorithm will be described more detailed in **Chapter 3** (Delta-Color Adjustment method and Segment Color Control method). The experimental results and evaluation indices will be described in **Chapter 4**. Finally, the conclusions and future works are given **in Chapter 5**.

Chapter 2

Prior Arts of High Dynamic Range Displays

The most primitive concept of HDR display systems and backlight dimming control will be reviewed.

2.1 High Dynamic Rang LCD with Locally Controlled LED Backlight

The contrast enhancement and power saving were limited by using 0D and 1D dimming backlight systems. Therefore, the high dynamic range LCD with locally controlled LED backlight was proposed.

2.1.1 Hardware Structure

The dynamic range of real-world environments exceeds the capabilities of conventional display technology by several orders of magnitude. Therefore, different dimensions of backlight systems (as show in Fig. 2-1) were proposed to display images with a dynamic range similar to that encountered in the real-world environments.

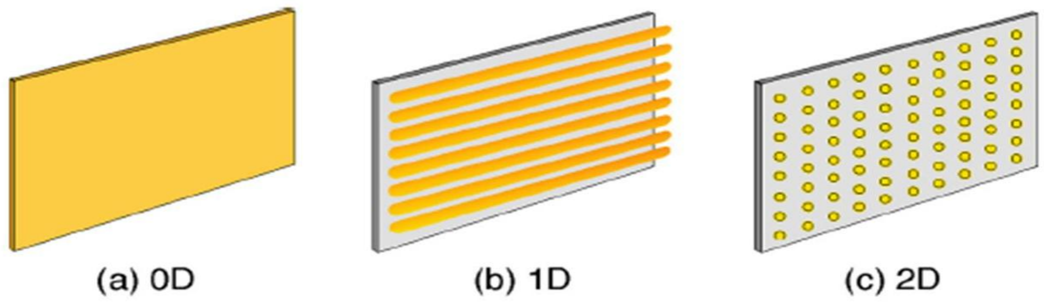


Fig. 2-1 Dimensional dimming of backlight systems [5]

The first display system with 0D backlight dimming was based on the combination of an

LCD panel and a digital light projector (DLP), and can be built from off-the-shelf components, as schematically shown in Fig. 2-2. The projector HDR display hardware provides a platform to present HDR images, but has several drawbacks. The major form factor constrains are due to the optical length required by the projector, thermal management, the power consumption, and cost.

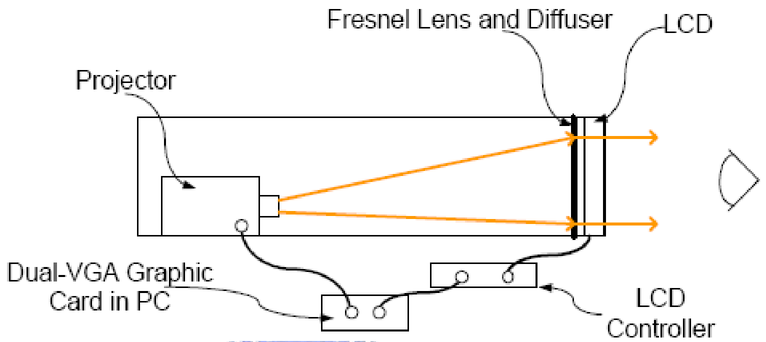


Fig. 2-2 Schematic of the HDR display including the projector, LCD and optics.

The second display system with 1D backlight dimming (line dimming) was proposed for overcoming the drawbacks of DLP typed HDR-LCD (as shown in Fig. 2-3). The 1D backlight dimming unit was applicable to Cold Cathode Fluorescent Lamps (CCFLs), Hot Cathode Fluorescent Lamps (HCFLs), and External Electrode Fluorescent Lamps (EEFLs). However, environment consciousness became more and more important in the recent years. Hence, the third display system with 2D backlight dimming (local dimming) was proposed. This backlight unit uses LEDs which can locally control and save more power consumption (as shown in Fig. 2-4). Therefore, the 2D backlight system is more suitable for usual office workspaces and commercial applications due to low power consumption [5].

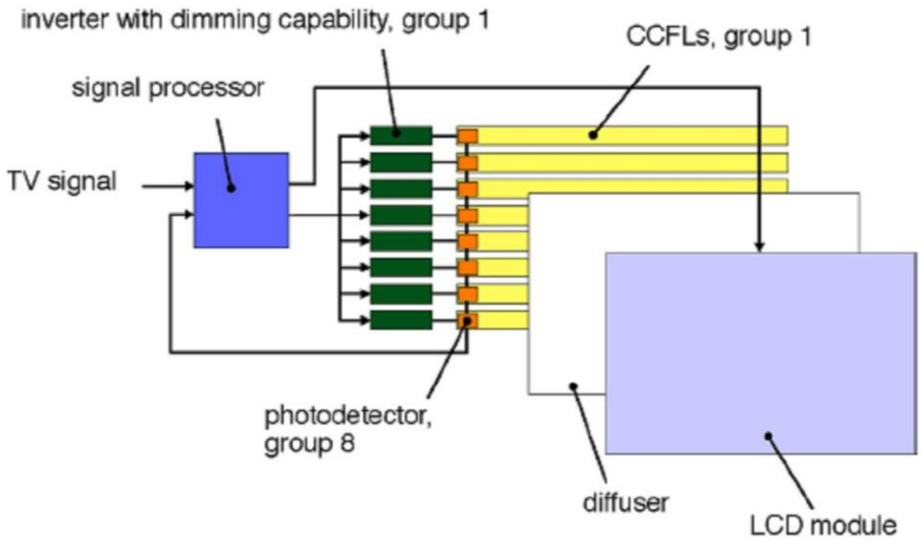


Fig. 2-3 CCFL backlight unit with 1D-dimming capability [5]

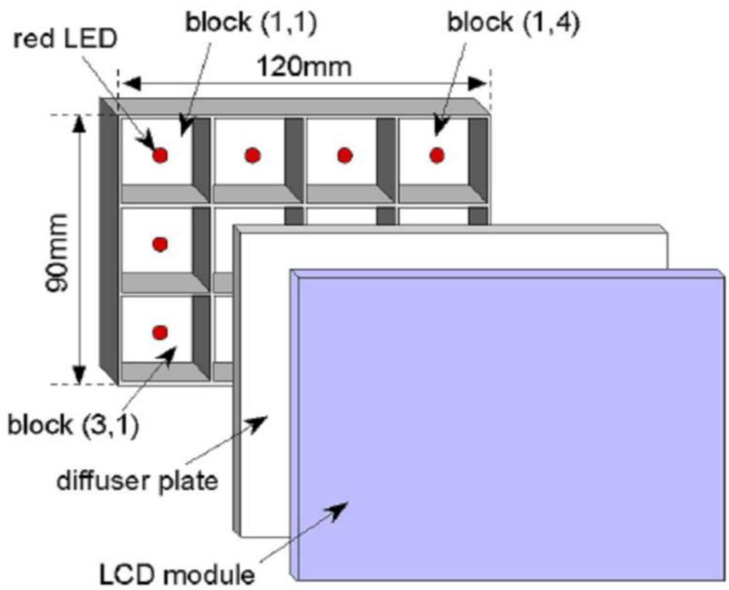


Fig. 2-4 LED backlight unit for 2D adaptive dimming [5]

For HDR-LCD TVs, the dynamic backlight with 2D dimming is a major trend in recent years. In this thesis, color backlight algorithm will be implemented on the optimized structure of 2D dimming.

2.1.2 Algorithm of HDR Systems

The limited dynamic range of displays has received much attention in recent years. The first step of the rendering algorithm of HDR displays is to calculate the square root of the original HDR image with intensity I (1) for enhancing the luminance (Fig. 2-5 [1]). The resulted image (2) thus derives the target intensities (I_L) for each individual LED (2a). The image samples to the resolution of the LED array for getting the intensity values of the LED’s. To map these intensity values into LED values by applying the inverse of the LED's response function r_1^{-1} to get gray-level values of LED’s (3). The LEDs now produce an image of intensity $r_1 [r_1^{-1} (I_L)] = I_L$, except that the image is actually blurred according to √I, the LED's point spread function (PSF) [1][4][6]. To simulate this blurring, convolve the intensities of LED array with the PSF (4) and divide above result from the original HDR image to get the target LCD transmittance (5). Finally by applying the inverse of the panel's response function r_2 to get the required LCD signals (6).

To obtain values of LCD signals, taking the overlap of the PSF into account. The PSF of an LED influences whole backlight panel. Therefore, solution can be approximated by single Gauss-Seidel iteration over neighboring LED pixels. This approach to compensate for differences between the LED values and the target image relies on the LCD panel. Therefore, the forward-simulated low-frequency image (4) generated by the LED panel is in order to get the LCD pixel values. The LED image is low-pass filtered.

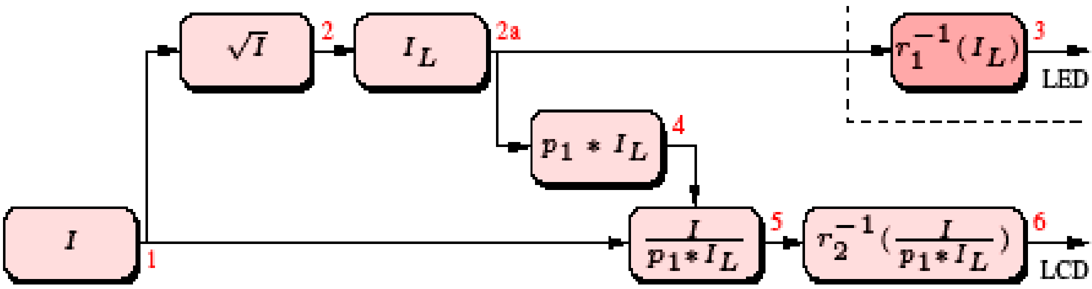
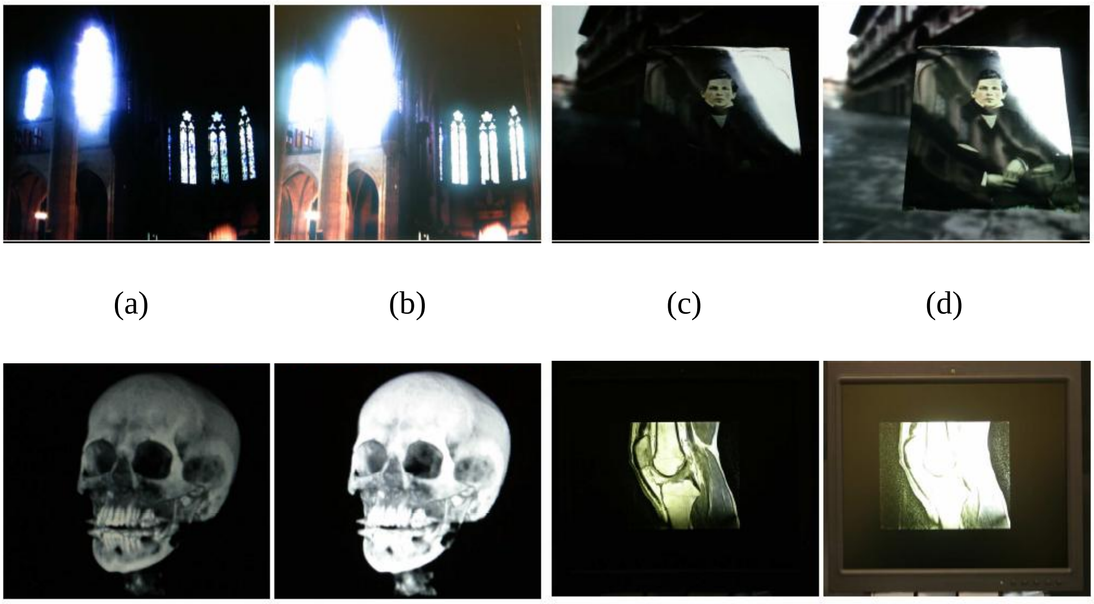


Fig. 2-5 Algorithm of conventional HDR display

The HDR display with backlight dimming reaches higher contrast ratio than that of the conventional display. The dark state actually has lower luminance, as shown in Fig. 2-6, the image details in the dark state are merely the same, or even worse than a traditional display.



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

(e) (f) (g) (h)

Fig. 2-6 Screen photographs of the different applications: (a)(b) HDR image viewer, (c)(d) interactive rendering, (e)(f) volume rendering, and (g)(h) medical image viewer.[1]

Besides contrast ratio, illumination also plays a significant role in visual perception from relevant literature. There are psychophysical and physiological evidences that absolute brightness information is important to human visual system [7]. Local contrast is generally used to convey the wealth of information about the real world. It is therefore necessary to preserve contrast information for displays. Furthermore, human sensitivity to luminance changes is not constant throughout the range of luminance, but is given by threshold-versus-intensity (TVI) function. The value of just noticeable luminance difference for given adaptation level was obtained from threshold-versus-intensity (TVI) function [7].

TVI function has been experimentally measured and shown in Fig. 2-7. Moreover, the adaptation level can vary across the image, which is known as local adaptation the TVI function [7].

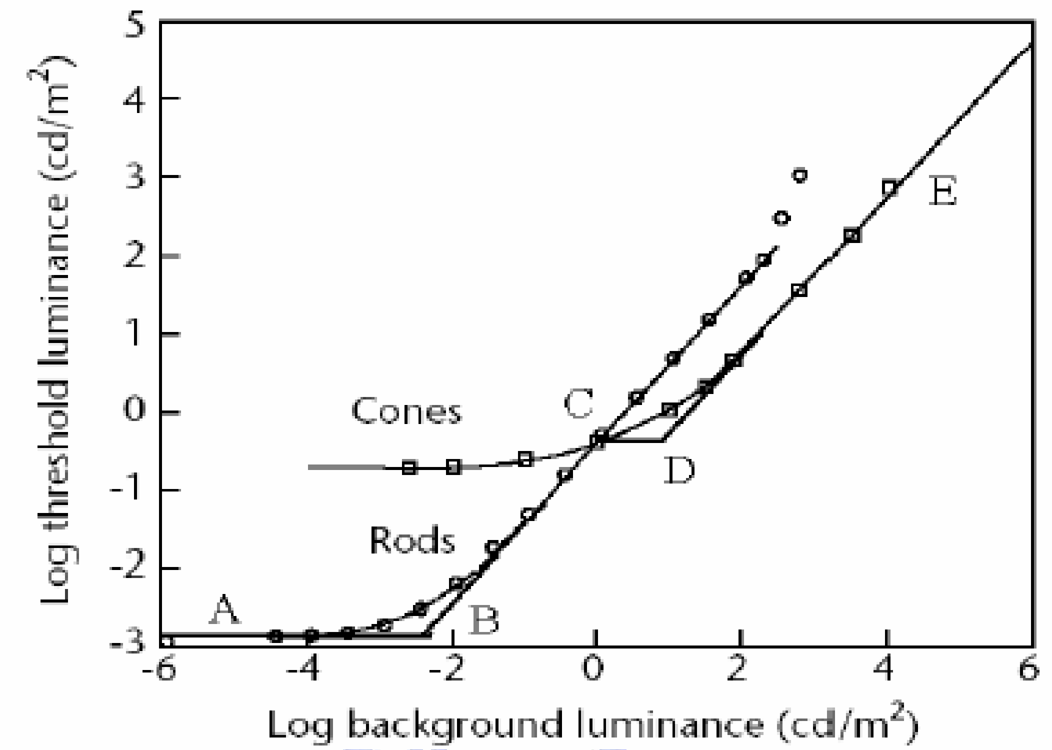
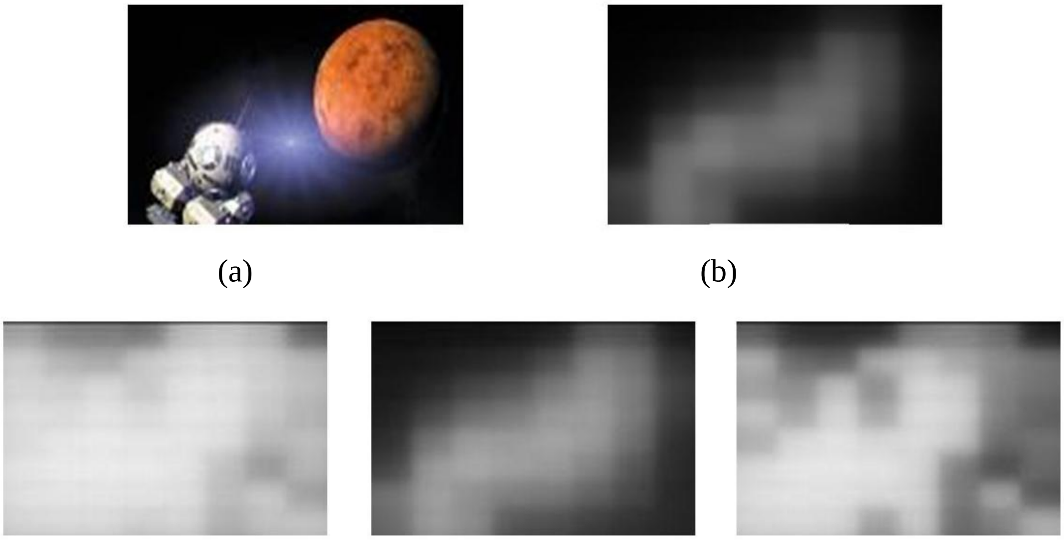


Fig. 2-7 TVI function [7]

The determination of backlight signals plays an important role in HDR algorithm, because it is one of the dominant factors in the output images of HDR-LCDs. A proper backlight determination will result in efficient brightness, high contrast ratio, and less image distortion. Therefore, different backlight determinations with intensity control were proposed in recent years.

The different backlight determinations, the average, maximum, square root, and Inverse of a Mapping Function (IMF) methods, with intensity control were compared and shown in Fig. 2-8.



(a) (b)

(c) (d) (e)

Fig. 2-8 (a) Target image (Robot); Convolution results of backlight signal determined by the (b) average, (c) maximum, (d) square root, and (e) IMF methods, respectively.

1. Average:

The average method is to calculate the average gray level of all maximum sub-pixel values in each BL region. By using this method, the contrast ratio is predicted to be the highest, but the output image may be dark due to the limitation of compensated LC transmittance (lower than 100%) and the lower luminance of the backlight signals.

2. Max:

The maximum method is to calculate the maximum gray level of the maximum sub-pixel values in each BL region. By this method, the maximum luminance and details of the image can be maintained well, but the dark state may be bright resulting in lower CR.

3. Root:

The root method, which was proposed by Brightside [1], is to calculate the average value of each BL region followed by taking the square-root operation on normalized backlight signals from the average values. The normalization changes the scale of backlight signals from “0~255” to “0~1”, and the square-root operation can enhance the whole backlight signals. By using this method, image details in dark state can be improved. But the method still has insufficient luminance in bright state.

4. Inverse of a Mapping Function (IMF):

The IMF method which was proposed by F.C. Lin, et al., [6] is to calculate the maximum of the maximum sub-pixel values in each BL region first, then using a different backlight modulation curve to modulate the backlight signal in different frames. By this method, the image not only produces a high-contrast backlight but also maintains the brightness and preserves the image details well.

2.2 Compensation of Liquid Crystal

Backlight dimming decreases the luminance of images in the HDR display system. Therefore, the transmittance of liquid crystal must be increased to compensate the luminance caused by backlight dimming [9]. The light spread function (LSF) of each LED groups (as shown in Fig. 2-9) is measured first. The way to determine the signal of liquid crystal (LC) is to convolve the backlight signal with the LSF for simulating a real backlight intensity distribution and deriving the compensational pixel values for the second panel- LC panel. The convolution process of intensity backlight distribution is shown in Fig. 2-10(a). The color backlight distribution was calculated by convolving the three dimensions of backlight signals with the same LSF individually, as shown in Fig. 2-10 (b).

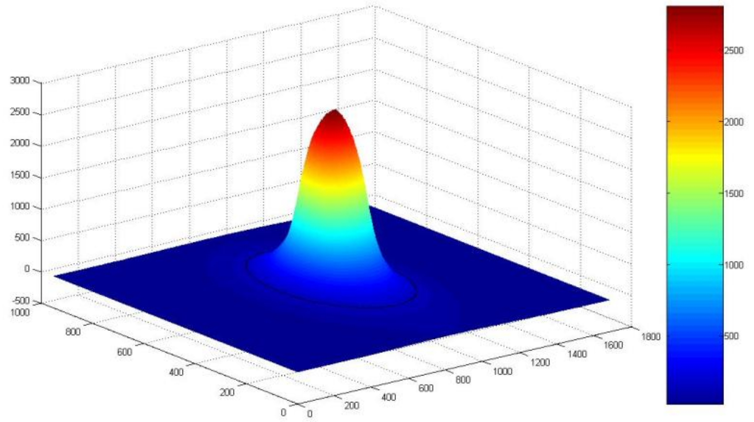
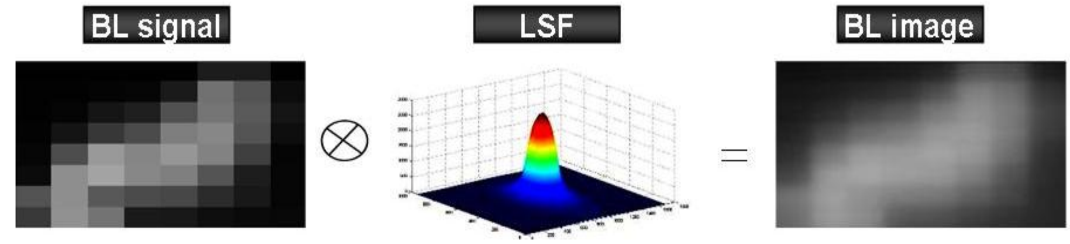
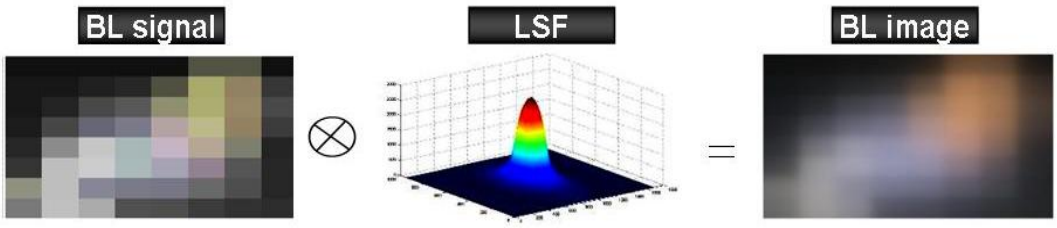


Fig. 2-9 Light Spread Function (LSF)



(a)



(b)

Fig. 2-10 (a) The simulation of intensity backlight distribution and (b) the simulation of color backlight distribution

2.3 Summary

The traditional backlight dimming did not consider three color dimensions of image information independently. Therefore, power consumption, color saturation and contrast ratio were limited. The objective of this thesis is to develop an optimized backlight algorithm with color control for enhancing contrast ratio, reducing power consumption, and enlarging color saturation in HDR-LCD systems

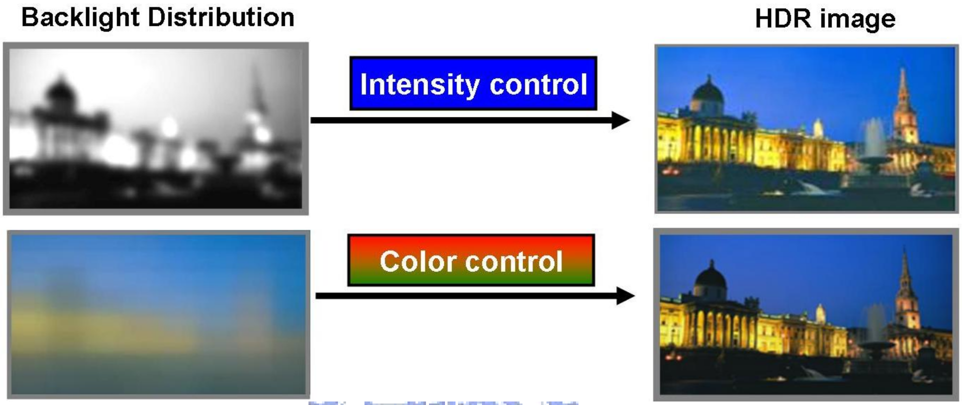


Fig. 2-11 Schema of an HDR system with intensity BL control and color BL control

Chapter 3

Color Backlight Algorithms for HDR-LCD TVs

Two color backlight algorithms with consideration of three dimensions of image information independently, the Delta-Color Adjustment (DCA) and the Segment Color Control (SCC) methods, are proposed for high dynamic range liquid crystal display (HDR-LCD) TVs.

3.1 Color Backlight Modulation

The determination of backlight signals played an important role in HDR-LCD system. Therefore, the HDR algorithm could use different backlight determinations to present HDR images as shown in Fig. 3-1. In this thesis, we propose two different color backlight control algorithms with consideration of three color dimensions of image information independently. The first method is Delta-Color Adjustment (DCA) which is depended on intensity control. The other one is the Segment Color Control (SCC) method which is independent of intensity control.

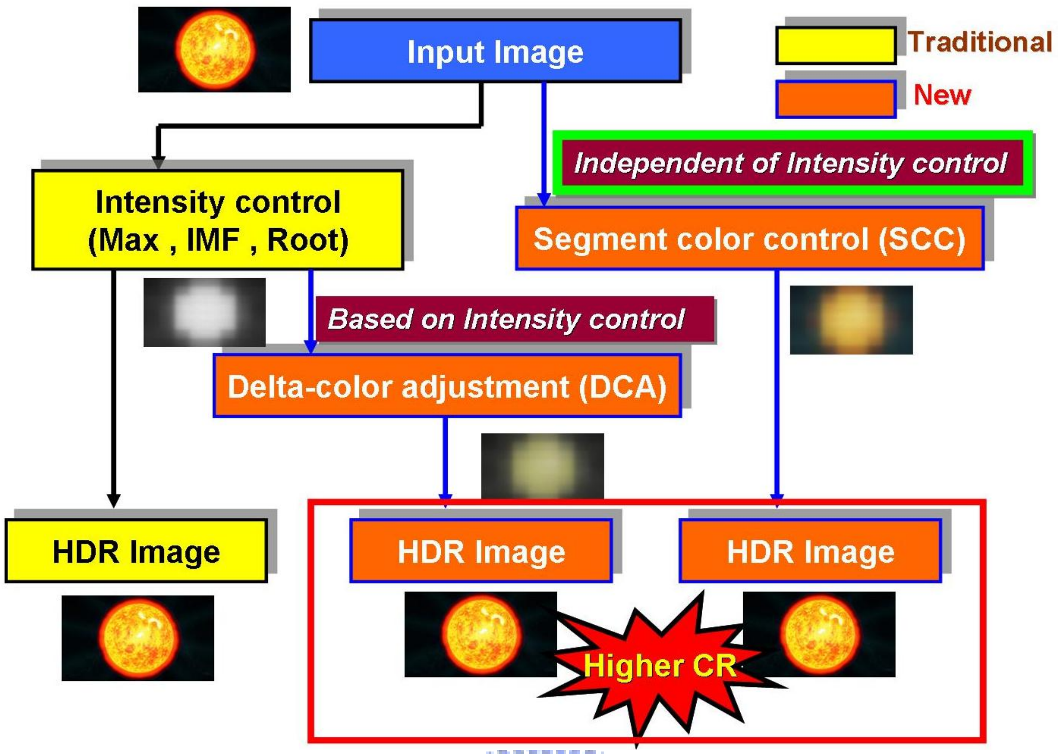


Fig. 3-1 Flow chart of HDR algorithm with different backlight determinations

3.1.1 Delta-Color Adjustment Method

An efficient color backlight control method, Delta-Color Adjustment (DCA), is to optimize the backlight image by modulating three dimensions (R, G, and B) backlight signals based on the adjusted results of intensity control. The DCA algorithm is shown in Fig. 3-2.

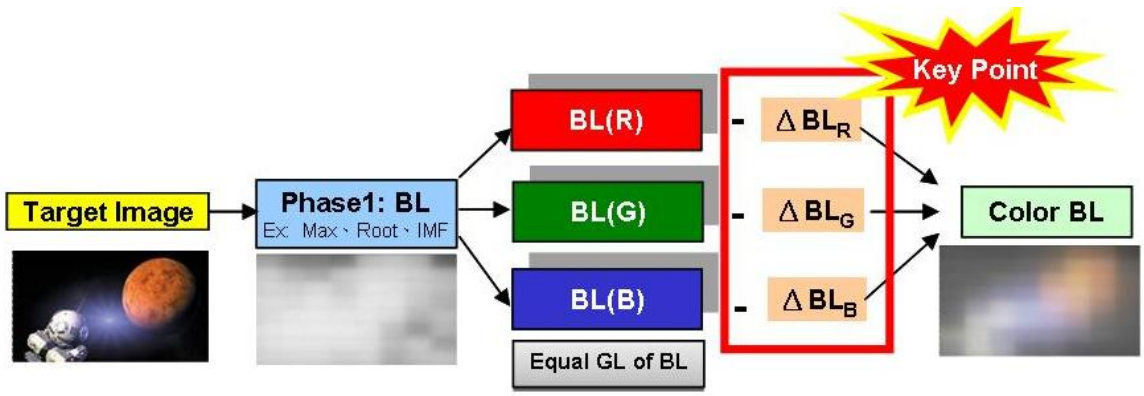


Fig. 3-2 Flow chart of the Delta-Color Adjustment algorithm

The intensity BL control was used as coarse backlight adjustments first. Then, the R, G, and B backlight signals were fine tuned to be the final color backlight signals. For coarse value, the backlight signal of each frame was determined by various intensity control method to be a [Phase 1: BL], such as the square root or IMF methods. Afterwards, the [Phase 1: BL] was divided into three equal gray levels (GL) for three-dimension backlight (BL(R), BL(G), and BL(B)). Next, the R, G, and B sub-pixel values in each backlight block were averaged for three-dimension (R, G, and B) BL individually to be the reference values. Finally, the references were used to decide three delta BL values (ΔBL_R, ΔBL_G, and ΔBL_B) for modifying the color-backlight signals. Therefore, the key of the DCA method was to determine the modified delta BL values ($\Delta BL_{R,\,G,\,B}$)

For modifying backlight signals, the BL gray-level (0~255) was divided into equal M parts to map the new value (1~M) as shown in (). After that, mapping the [Phase 1: BL] of each backlight block to obtain the new mapping value ($MAP_{intensity}$). Next, the average gray level values of R, G, and B pixels in each backlight block were calculated individually, and used the same look-up table (Table 3-1) to map three reference values ($MAP_{r,g,b,}$), as shown in Eq. (1). Furthermore, a N value was set as the threshold value for adjustment (Eq. (2)), if the three transient BL values ($T_{r,g,b}$) were larger than N value, the RGB backlight signals would be dimmed, otherwise would maintain the same value as intensity control[Phase 1: BL]. Finally, multiplying 256/M by three delta values ($D_{r,g,b}$) individually to get three delta BL values ($\Delta BL_{R,G,B}$), as shown in Eq. (3).

$$MAP_{intensiy} - MAP_{r,g,b} = T_{r,g,b} \; ; \qquad (1)$$

$$\text{If } T_{r,g,b} > N \text{ (Threshold)} \rightarrow \quad D_{r,g,b} = MAP_{intensiy} - MAP_{r,g,b} - N, \;\; \text{else}_{\;r,g,b=}0 \qquad (2)$$

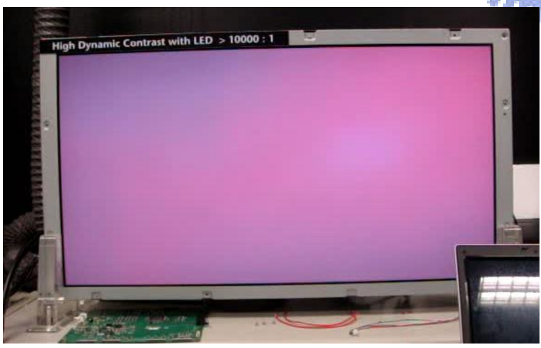
$$\Delta BL_{R,G,B} = D_{r,g,b} * 256/M \qquad (3)$$

Different M (adjustment division) and N (adjustment threshold) values would influence image quality and power consumption in the DCA method. Therefore, a 37” HDR-LCD which was divided into 8×8 zones with 1920×1080 MVA-LC panel by using locally controlled color backlight (Fig. 3-3), was set up to optimize the suitable M and N values. From commercial point, the DCA method could apply to various intensity control methods.

Table 3-1 The Lookup table of the Delta-Color Adjustment algorithm

Lookup table

BL value	$MAP_{intensity}$ or $MAP_{r,g,b}$
$(\frac{256}{M}\times(M-1)-1)\sim(\frac{256}{M}\times M-1)$	M
$(\frac{256}{M}\times(M-2)-1)\sim(\frac{256}{M}\times(M-1)-1)$	M-1
⋮	⋮
$(\frac{256}{M}\times 2-1)\sim(\frac{256}{M}\times 3-1)$	3
$(\frac{256}{M}-1)\sim(\frac{256}{M}\times 2-1)$	2
$0\sim(\frac{256}{M}-1)$	1



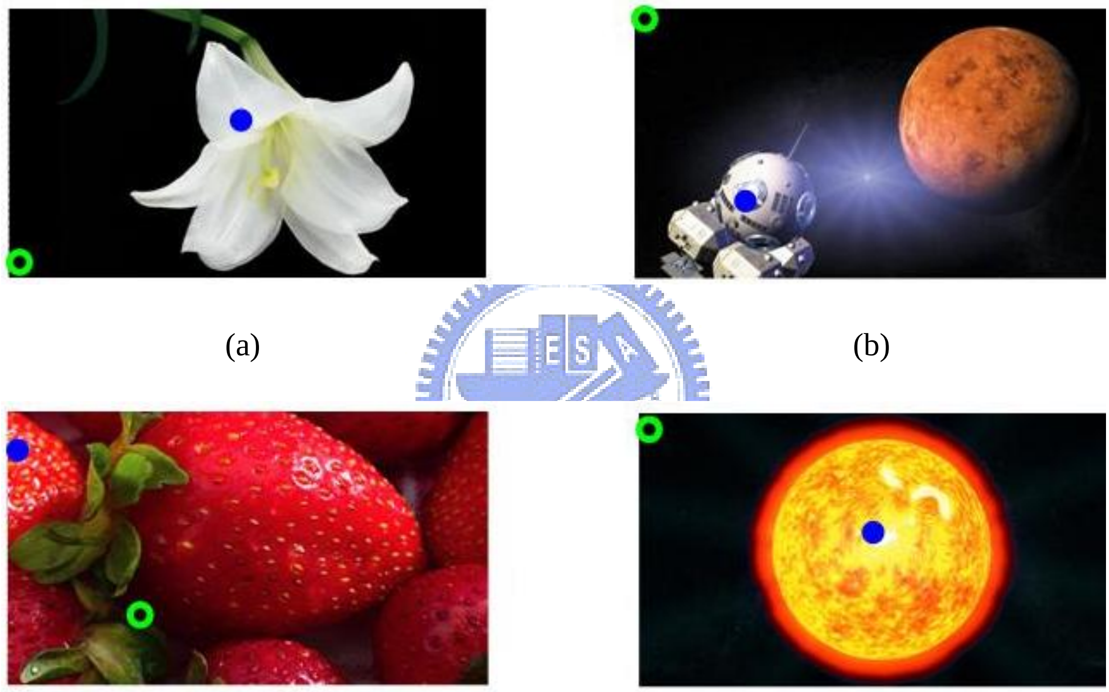
The Specification of Test Panel	
Device	HDR-LCD
Backlight Module	8x8 RGB LED Zones
Resolution	1920x1080
LC Mode	MVA

(a) (b)

Fig. 3-3 (a) A 37” HDR-LCD panel with color control backlight and (b) the specification of a 37” HDR-LCD panel

Due to the high dynamic range of human vision, the main purpose of the HDR system was to produce a high contrast ratio (CR) image to match the human vision range [10]. In our experiment, CR was measured by using a luminance analyzer, CA-210 [11], with a measuring area of 27mm in diameter (covering about 12,834 pixels).

Four test images, the high CR target image, *Lily*, the dark target image, *Robot*, the colorful image, *Strawberry*, and the high detail image, *Sun*, shown in Fig. 3-4 were demonstrated on a 37” 1920×1080 resolution HDR-LCD TV with 8×8 backlight zones. The positions of maximum luminance (L_{max}) and minimum luminance (L_{min}) are respectively marked with a blue solid dot and a green hollow dot in Fig. 8.



(a) (b)

(c) (d)

Fig. 3-4 Test images with their CR measuring points, L_{max} and L_{min} are respectively marked with a blue solid dot and a green hollow dot. (a) Lily (high CR image), (b) Robot (dark image), (c) Strawberry (colorful image), and (d) Sun (high detail image)

The key point of the DCA method was to determine suitable delta BL values (ΔBL_R, ΔBL_G, and ΔBL_B). For image performance, the DCA method would be affected by M (adjustment division) and N (adjust threshold). For optimizing the M and N values, the experimental flow is shown in Fig. 3-5. In the first four different images, *Lily*, *Robot*, *Sun*, and

Strawberry, were chosen as experimental images. In addition, the inverse of a mapping function (IMF) method was chosen as the intensity control method: [Phase 1: BL] because that IMF has optimized image performance with low power consumption [8]. Then the experiment was implemented on a 37'' HDR-LCD panel to find the most suitable M and N values. Eventually, power and human score for image details were selected as evaluation indices.

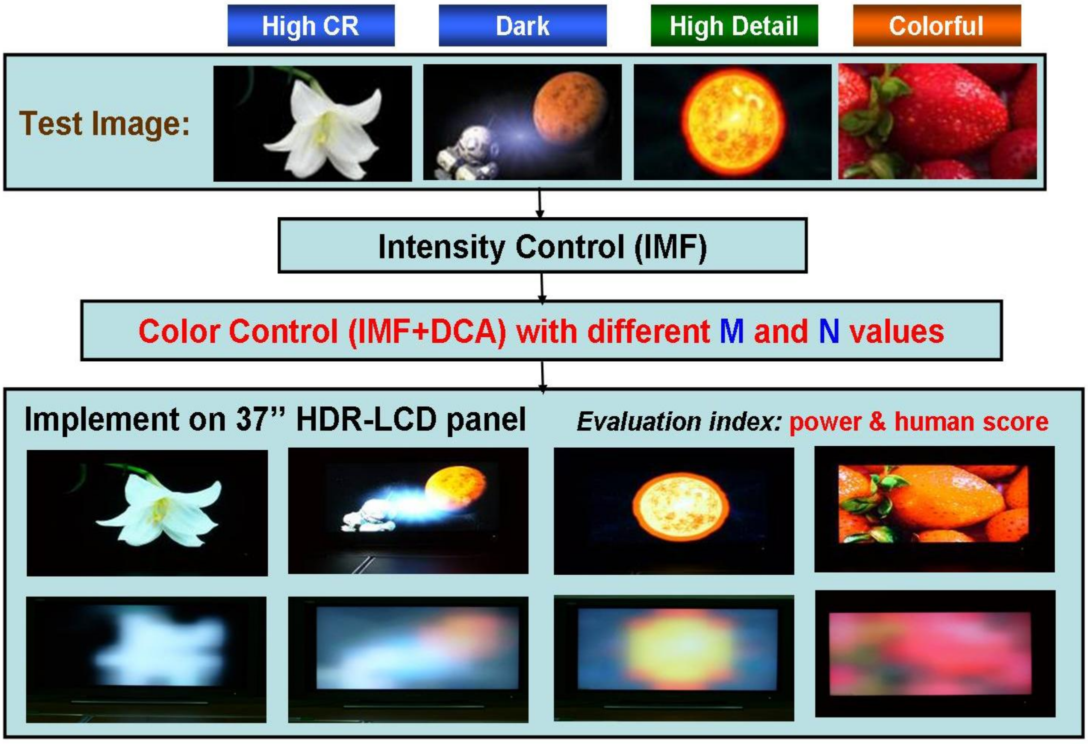


Fig. 3-5 Experimental flow for optimizing delta BL values (M and N)

A conventional evaluation index for the image details of an HDR-LCD was distortion ratio which did not consider human vision. Therefore, human adjust score was proposed to evaluate the image details by psychophysics experiments. The image details were evaluated by seven different observers. They have normal color vision with ages range from 24 to 30 years. The data of observers are summarized in Table 3-2. The adjust range of human score was 0 to 10 (10 is the best).

Table 3-2 Characteristics for each observer

Observer	Age	Male/Female	Color vision
GW	25	Male	Normal
SC	30	Male	Normal
RC	28	Male	Normal
LL	24	Male	Normal
RS	24	Female	Normal
RB	24	Male	Normal
ZS	26	Male	Normal

The experimental result of human score is shown in Fig. 3-6. Obviously, the larger N would get the higher image quality. Besides, the average power consumption of four different images was measured as shown in Fig. 3-7. As a result, image details and power consumption were traded-off. To obtain the highest image quality (human score=10) and the lowest power consumption, the optimizing values were decided as M=16 and N=6 which could get the best balance point with power consumption and image quality by using the DCA method.

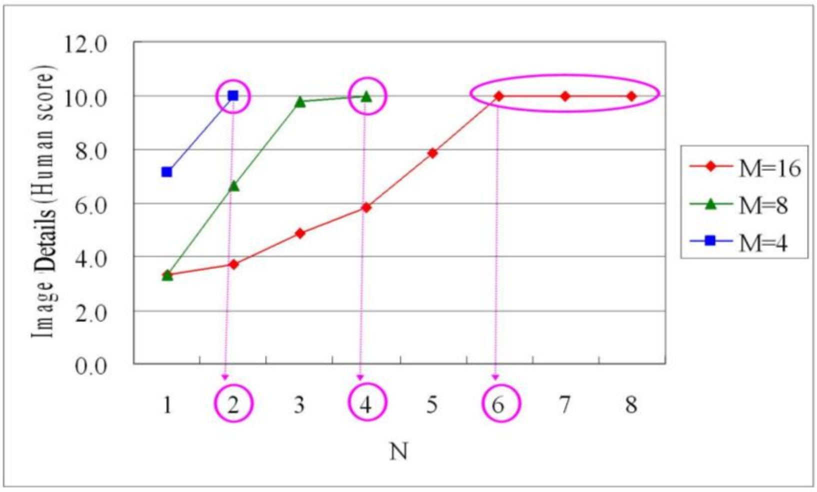


Fig. 3-6 Average image quality score of IMF +DCA (M=16, 8 and 4)

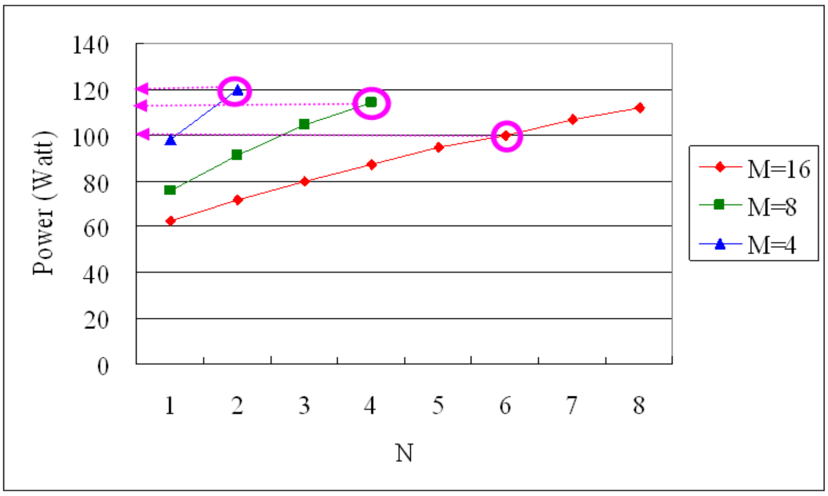


Fig. 3-7 Average power consumption of IMF +DCA (M=16, 8 and 4)

The concept of the DCA method was based on various intensity control methods. Besides, the DCA method got modified color-backlight by combining suitable delta values. From the experimental results, two major parameters, M (adjustment division) and N (adjust threshold), of the DCA method were selected as M=16 and N=6 respectively by optimizing image quality and power consumption. However, the IMF +DCA (M=16 and N=6) method consumed more hardware resources due to accumulating histogram values for IMF.

3.1.2 Segment Color Control Method

The IMF+DCA method is more complicated because IMF has to accumulate histogram values. Therefore, the Segment Color Control (SCC) method was proposed to resolve the complexity of IMF+DCA. At first, each block of three dimensions image (R, G, and B) was decided to map different segments by using the average algorithm individually. Then, each segment was processed by various optimized algorithms.

For instance, segment values (i.e., Average (A) =2, Root (R) =2, and Max (M) =4) were decided. The first region and the second region (GL 0~63) were processed by average algorithm. Then, the third region and the fourth region (GL 64~127) were processed by the root algorithm. Eventually, remainder regions (GL 128~255) were processed by the maximum algorithm (as shown in Fig. 3-8). The motivation of the SCC method was to combine the advantages of three algorithms (average, root, and maximum). First, the average algorithm could decrease luminance in dark state. Second, the root algorithm could enhance the whole backlight signals in each frame. Finally, the maximum algorithm could maintain the brightness and preserve the image details in bright state.

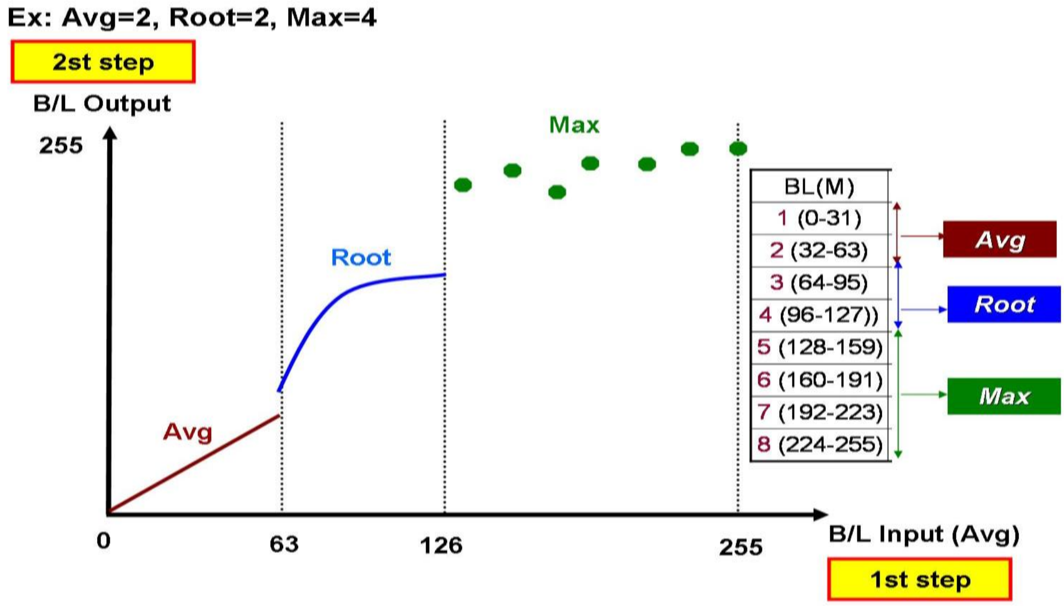


Fig. 3-8 B/L curve of the SCC method

For optimizing the segment values (A, R, and M), the experimental flow is shown in Fig. 3-9. At first, four different images were chosen as experimental target images. Then the SCC method with different segment values (A, R, and M) was implemented on a 37” HDR-LCD panel to find the most suitable segment values (A, R, and M). Image details were also evaluated by human observation score. The experimental results of human score were shown in Fig. 3-9. Obviously, the highest image quality (human score=10) was decided as A=1, R=2, and M=5, which could get the best image quality by using the SCC method.

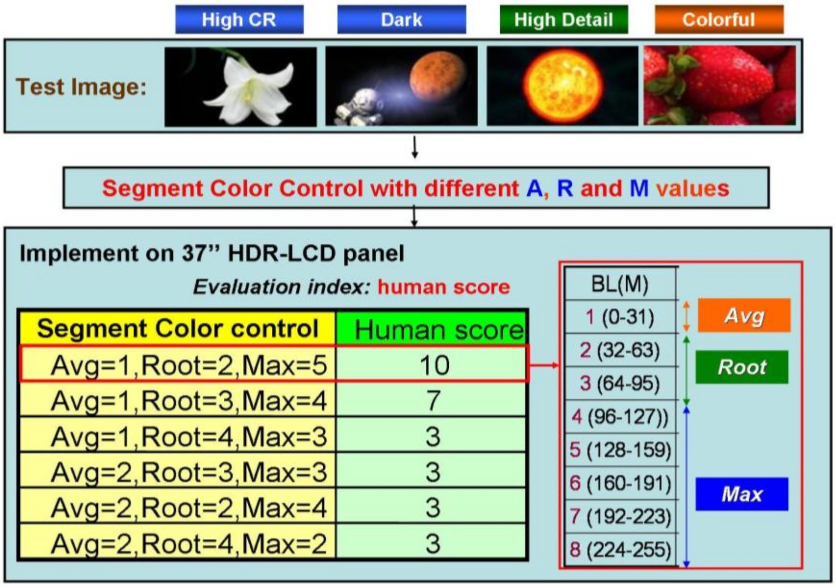
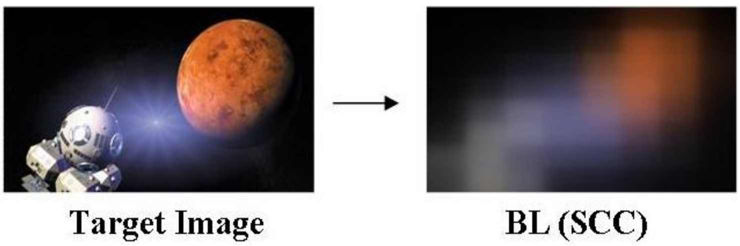


Fig. 3-9 The experimental flow of segment values (A, R, and M)

The concept of the SCC method can be independent of intensity control methods, which can reduce one step compared to that of the DCA method, as shown in Fig. 3-10. Then, the SCC method can be modified color-backlight by suitable segment values (A, R, and M). Finally, the experimental results of the SCC method were selected as A=1, R=2 and M=5 by optimizing image quality. Therefore, SCC (A=1, R=2, and M=5) not only consumed less hardware resources but also maintained image details.

(a)



(b)

Fig. 3-10 Flow chart of the (a) DCA and (b) SCC methods

3.2 Summary

Two different color backlight control algorithms of the Delta-Color Adjustment (DCA) and Segment Color Control (SCC) methods were proposed to optimize the backlight algorithms with intensity control. The DCA method was based on intensity control to optimize, whereas the SCC method was independent of intensity control. Therefore, the SCC method uses less steps compared to that of the DCA method to get color backlight, but the DCA method applies to various backlight algorithms with intensity control.

Chapter 4

Experimental Results of Static Images

Two proposed color backlight control algorithms have been implemented on a 37" HDR-LCD to evaluate the static images. In this chapter, image detail, power, and contrast ratio are chosen as evaluation indices to demonstrate the advantages of our proposed algorithms.

4.1 Instrument and Hardware

In the experiment, the CR was measured by using a luminance analyzer, CA210 [11], with a measuring area of 27mm in diameter (covering 12,834 pixels approximately).

Fig. 4-1 Luminance analyzer-CA210

The CA210 uses an optical system for measuring luminance and chromaticity of LCD panels. The main components of the optical system are the objective lens, optical fiber block, on-chip lenses, and sensor, as shown in Fig. 4-2. The light form the light source is focused on the receiving window of the optical fiber block. The focused light is mixed inside the optical fiber block and split into three parts, which are then guided to the receiving areas of the x, y, z sensors. Here, the light is further focused by the on-chip lenses onto the sensors themselves.

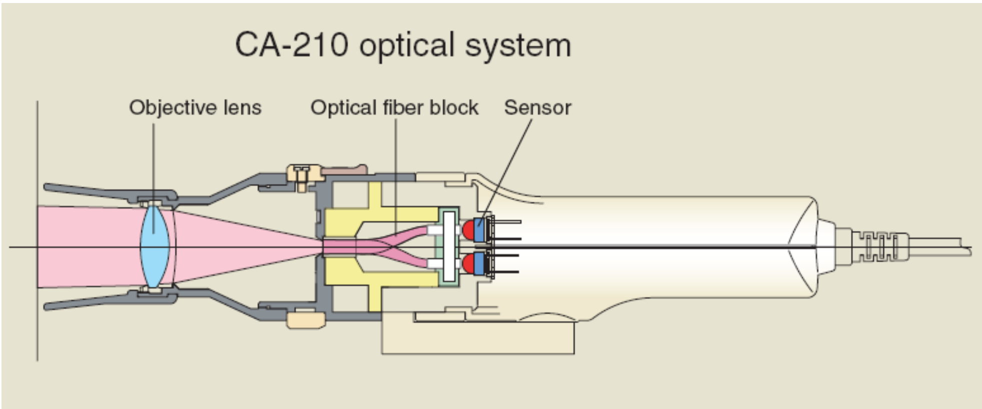


Fig. 4-2 Optical system of CA210

Two color backlight control algorithms were applied on a 37” HDR-LCD TV supported by AU Optronics (AUO) Corporation. This panel is 1920×1080 (HDTV) resolution with 8×8 backlight zones. Each backlight zone can locally dim three primary LEDs (R, G, and B) independently, as shown in Fig. 4-3.

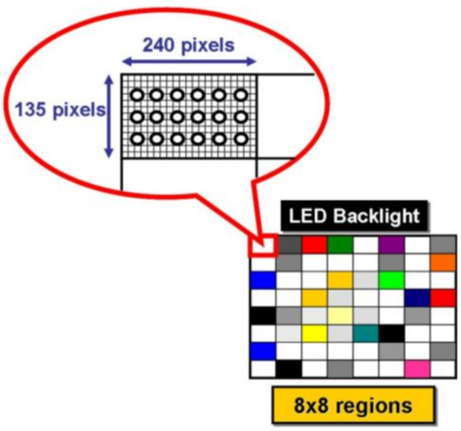


Fig. 4-3 Platform of the 37” HDR-LCD TV with color control

Backlight and liquid crystal signals were controlled by the FPGA control systems of the 37” HDR-LCD panel. The backlight signal was controlled by using I^2C-Bus which is internal bus that provides the communication between integrated circuits in a system to control FPGA [12]. Besides, liquid crystal signal was delivered by Digital Visual Interface (DVI), as shown in Fig. 4-4.

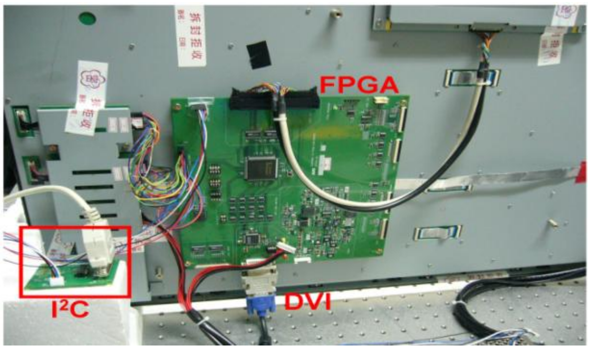


Fig. 4-4 Control systems of the 37” HDR-LCD TV

The maximum color gamut of the HDR-LCD TV could be enlarged from 107.7% to 125.4% NTSC by using color BL control, as shown in Fig. 4-5. Besides, the power consumption of the HDR-LCD TV could be reduced by using color control. In the experimental panel, three primary LEDs (R, G, and B) consumed different power consumption, as shown in Fig. 4-6. Therefore, red LEDs could save three watts, green LEDs could save five watts, and blue LEDs could save four watts by reducing per 16 gray levels.

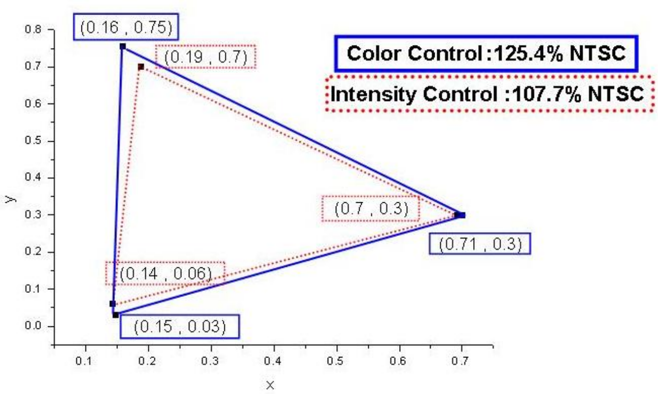


Fig. 4-5 The color gamut of the 37” HDR-LCD TV

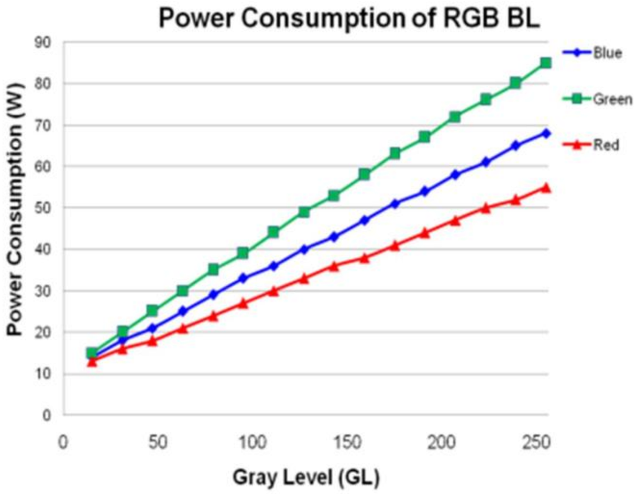
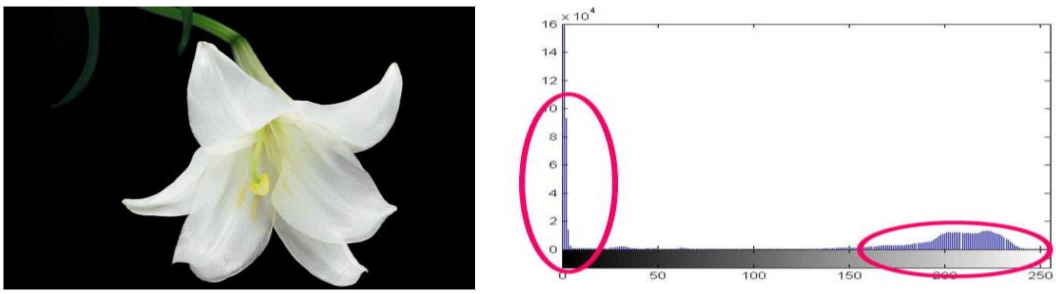


Fig. 4-6 The power consumption of the 37” HDR-LCD TV

4.2 Static Testing Images

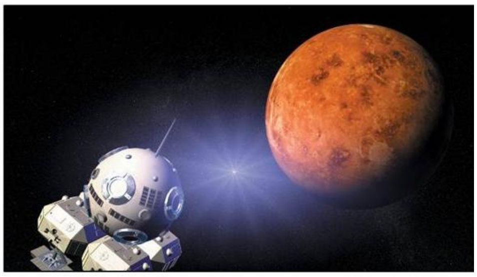
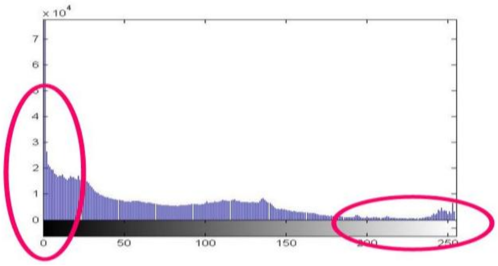
(a) In order to adjust the image qualities by using various backlight algorithms, three indices, “image details”, “power consumption”, and “contrast ratio” were been utilized. Therefore, four different static images, *Lily*, *Robot*, *Sun*, and *Strawberry* were chosen as experimental target images, as shown in Fig. 3-4. Referring to

Fig. 4-7 (b) and Fig. 4-8(b), the target images, *Lily and Robot*, were the high contrast ratio images. Next, the target image, *strawberry*, has more red content, as shown in Fig. 4-9. Finally, the target image, *sun*, which has high image details could be magnified to compare image details, as shown in Fig. 4-10.



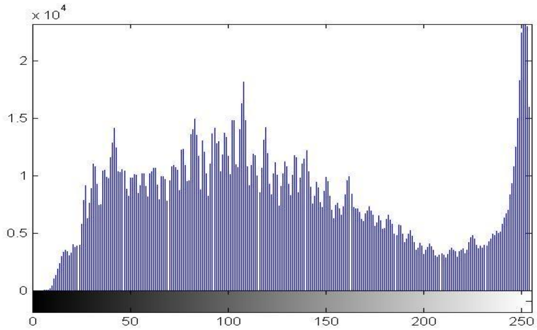
(b) (b)

Fig. 4-7 (a) The high CR image and (b) the histogram of the target image- *Lily*

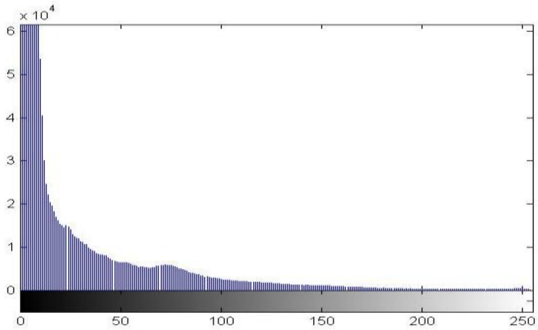
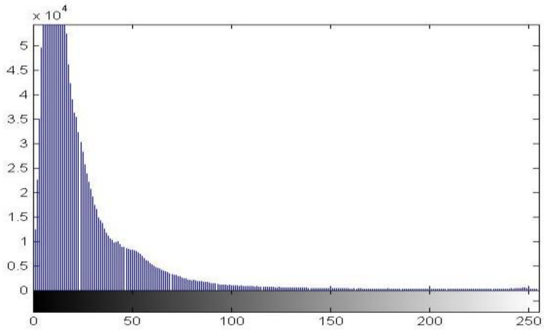
 

(a) (b)

Fig. 4-8 (a) The high CR image and (b) the histogram of the target image- *Robot*

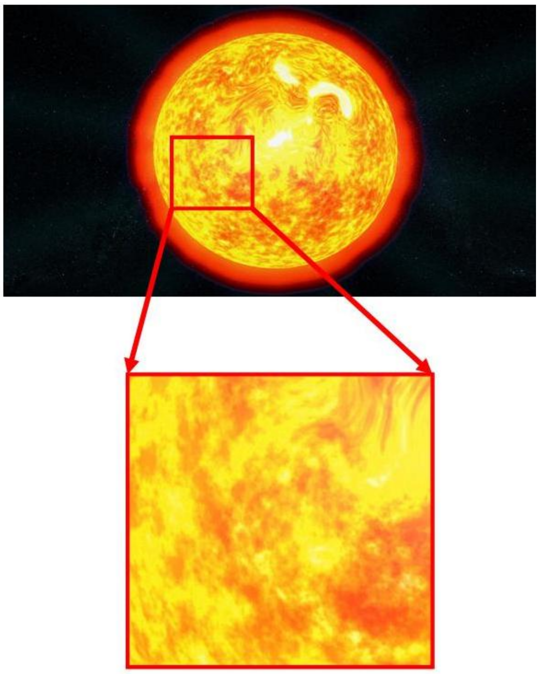
 

(a) (b)

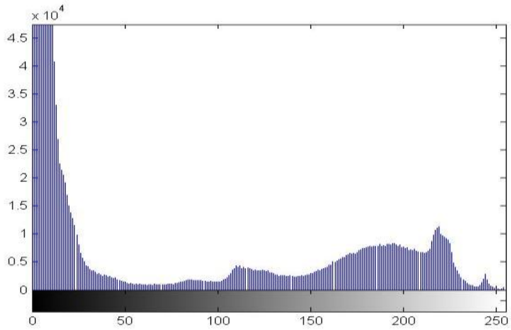
 

(c) (d)

Fig. 4-9 (a) The colorful image- Strawberry, (b) the histogram of red, (c) green, and (d) blue component.



(a)

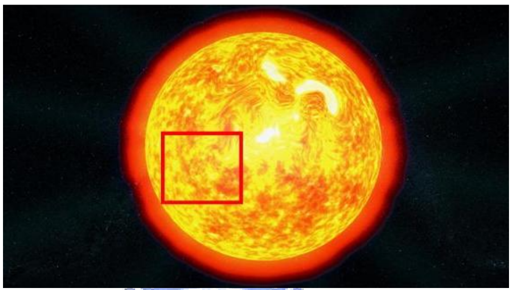


(b)

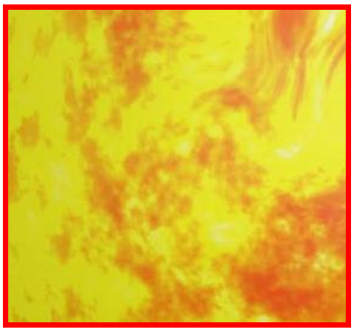
Fig. 4-10 (a) The red rectangle of high detail image are magnified and (b) the histogram of the high detail image- *Sun.*

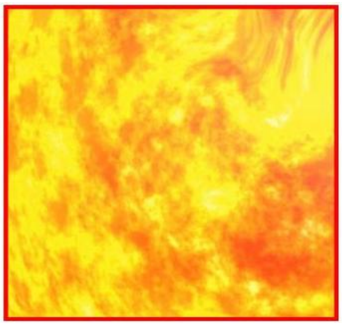
4.3 Image Details

The high detail image, *Sun*, was locally magnified and shown in Fig. 4-11. The image details in the high brightness region were almost preserved by using Max, IMF, IMF+DCA (M=16, N=6), and SCC (A=1, R=2, M=5). Therefore, the two color backlight control methods, the Delta-Color Adjustment method and the Segment Color Control method, could keep the image details.

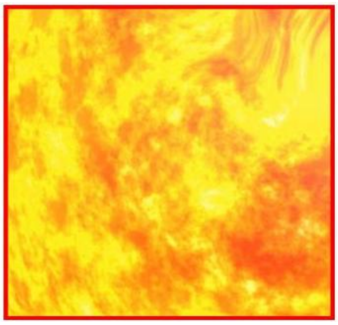


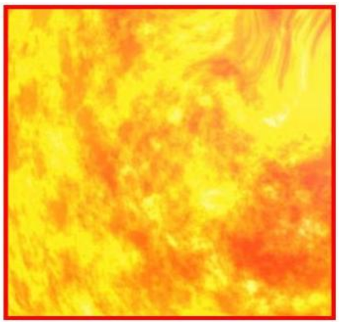
(a)





(b) (c) (d)





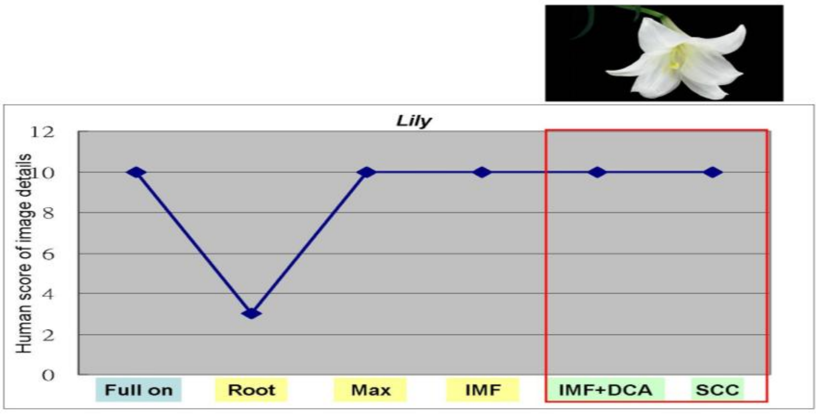
(e) (f)

Fig. 4-11 The results of the magnified section in the test image-*Sun*. (a) The target image, (b) root method, (c) max method, (d) IMF method, (e) IMF+DCA (M=16,N=6), and (f) SCC (A=1, R=2, and M=5), respectively.

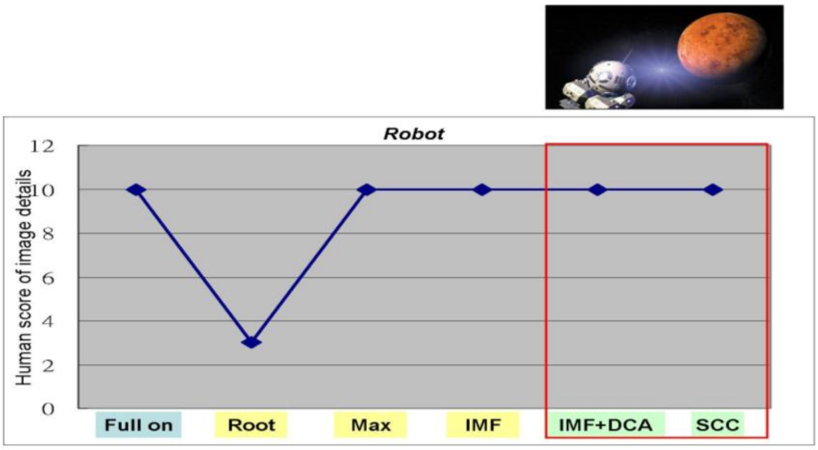
There is no suitable index to describe image details in HDR systems. Therefore, human evaluation score was proposed to evaluate image details by phychophysical experiments of seven observers (score= 0~10, and 10 is the best) with four different images, *Lily*, *Robot*, *Strawberry*, and *Sun*, and the results are shown in Table 4-1and Fig. 4-12. The root method had the lowest human score (score= 3) with the four test images. Besides, human score of three methods was the same (score= 10) that represents imperceptive image distortion.

Table 4-1 Human score of *Lily*, *Robot*, *Strawberry*, and *Sun* by using six different backlight algorithms.

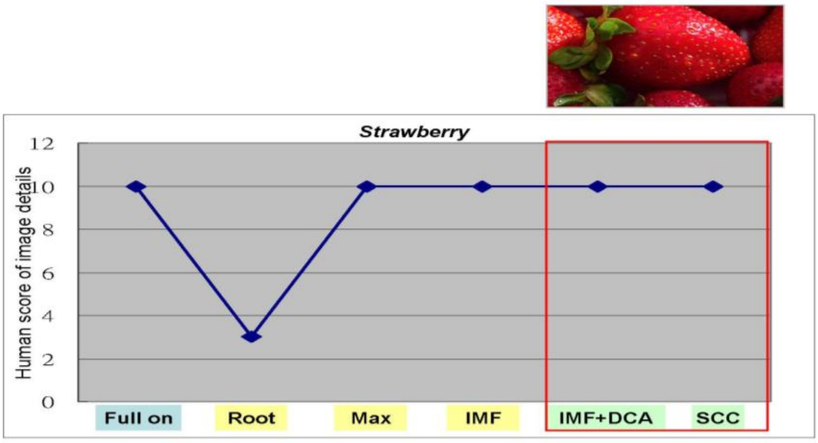
Backlight Algorithm	Lily	Robot	Strawberry	Sun
Full on	10	10	10	10
Root	3	3	3	3
Max	10	10	10	10
IMF	10	10	10	10
IMF+DCA(M=16,N=6)	10	10	10	10
SCC(A=1,R=2,M=5)	10	10	10	10



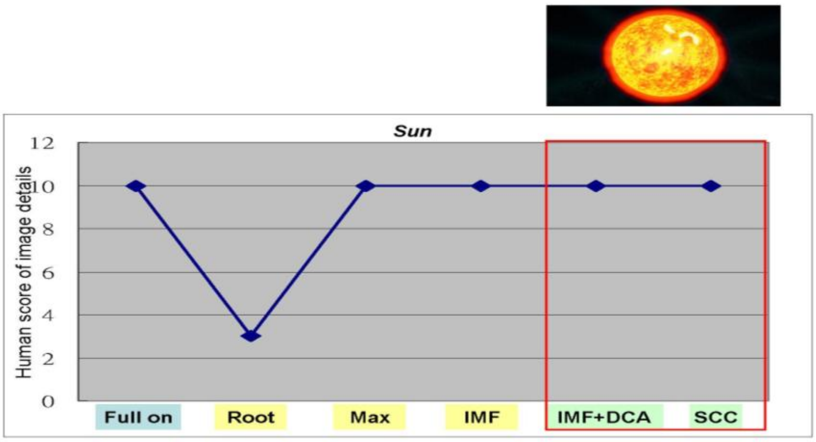
(a)



(b)



(c)



(d)

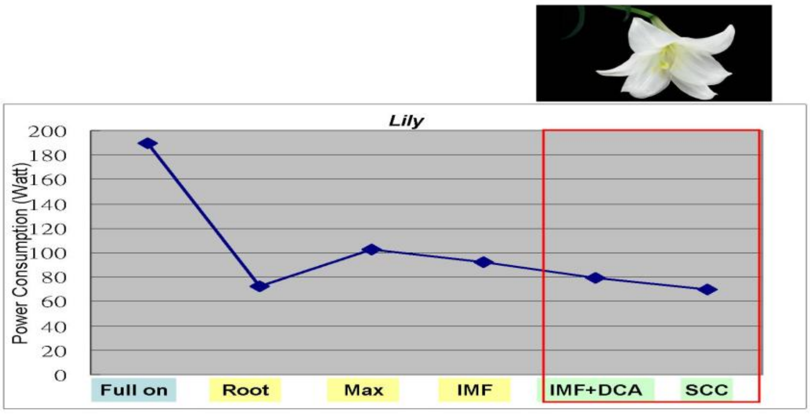
Fig. 4-12 Comparison of human score of *(a)Lily*, *(b)Robot*, *(c)Strawberry*, and *(d) Sun* by using six different backlight algorithms.

4.4 Power Consumption

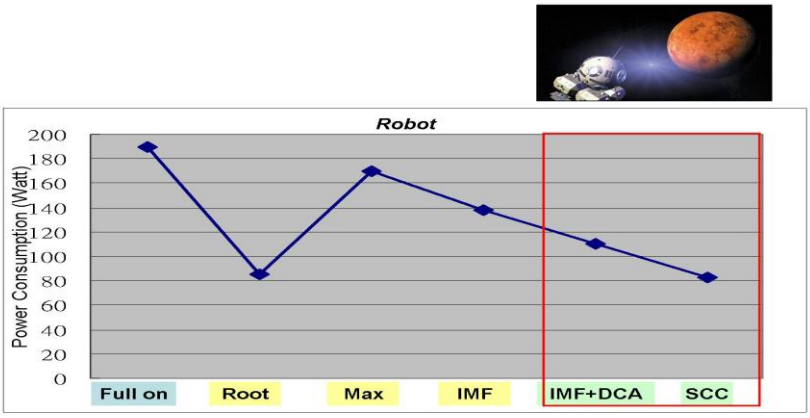
Color backlight algorithm can also result in lower power consumption. The power consumption by different backlight algorithms is compared and results are listed in Table 4-2 and shown in Fig. 4-13. The two color backlight algorithms can save much power relative to conventional full-on backlight and gray backlight.

Table 4-2 Power consumption of *Lily, Robot, Strawberry,* and *Sun* by using six different backlight algorithms. (Unit: watt)

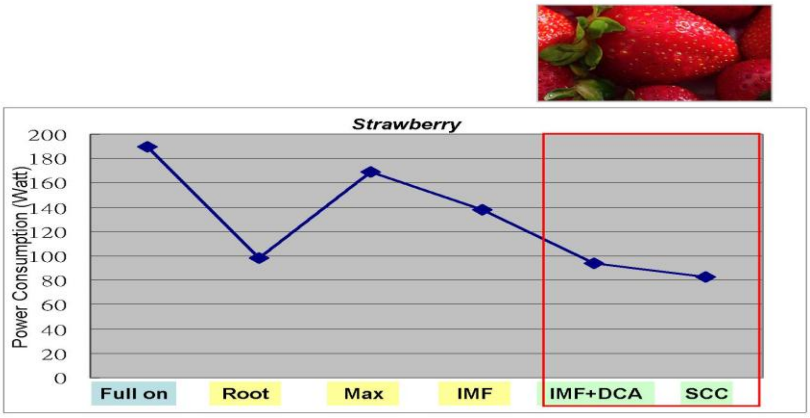
Backlight Algorithm	**Lily**	**Robot**	**Strawberry**	**Sun**
Full on	190 (100%)	190 (100%)	190 (100%)	190 (100%)
Root	72 (38%)	85 (45%)	98 (52%)	99 (52%)
Max	103 (54%)	170 (89%)	169 (89%)	179 (94%)
IMF	92 (48%)	138 (73%)	138 (73%)	170 (89%)
IMF+DCA(M=16,N=6)	79 (42%)	110 (58%)	94 (49%)	116 (61%)
SCC(A=1,R=2,M=5)	70 (37%)	83 (44%)	83 (44%)	82 (43%)



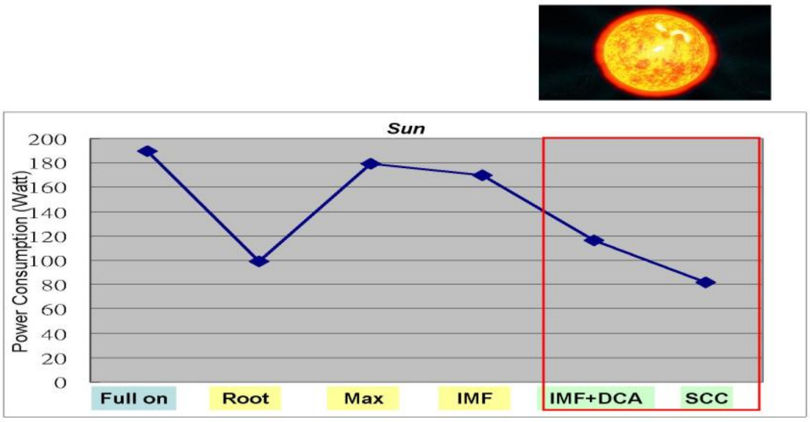
(a)



(b)



(c)



(d)

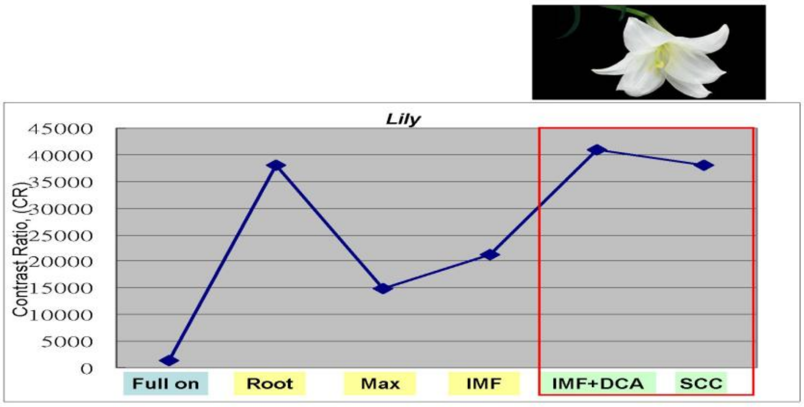
Fig. 4-13 Comparison of power consumption of *(a) Lily*, (b) *Robot*, (c) *Strawberry*, and (d) *Sun* by using six different backlight algorithms.

4.5 Contrast Ratio

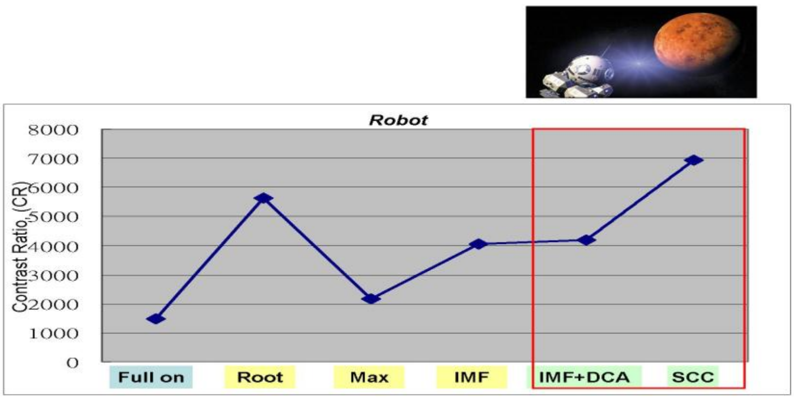
HDR system can also yield a high contrast ratio (CR) image to satisfy human vision system in the real world with high dynamic range. The positions of maximum luminance and minimum luminance were shown in Fig. 3-4. Consequently, CR of the images was measured by using a luminance analyzer, CA210 [11], as shown in Table 4-3.

Table 4-3 Contrast ratio of *Lily*, *Robot*, *Strawberry*, and *Sun* by using six different backlight algorithms.

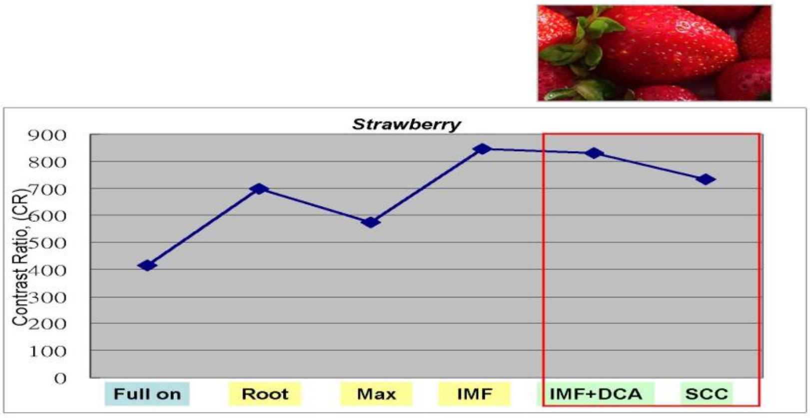
Backlight Algorithm	Lily	Robot	Strawberry	Sun
Full on	1352	1465	417	1394
Root	38140	5637	698	4268
Max	14947	2156	574	1614
IMF	21230	4038	847	1800
IMF+DCA(M=16,N=6)	40870	4182	829	2704
SCC(A=1,R=2,M=5)	38060	6944	735	5226



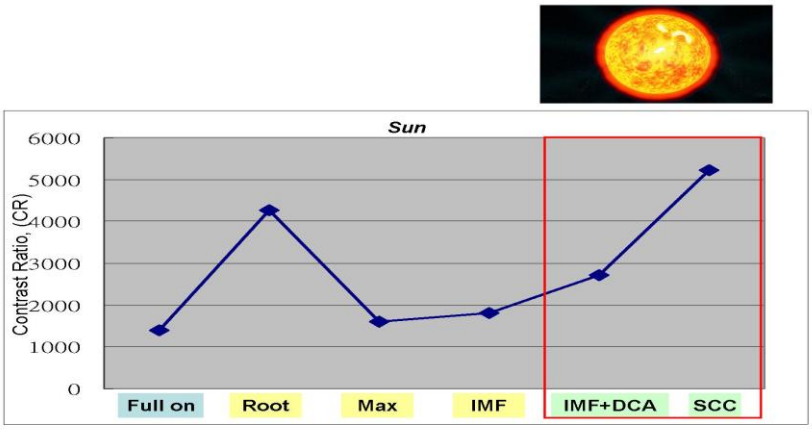
(a)



(b)



(C)



(d)

Fig. 4-14 Contrast ratio of *(a) Lily*, (b) *Robot*, (c) *Strawberry*, and (d) *Sun* by using six different backlight algorithms.

Compared CR values of these methods, although root method has high CR, but the human score is too low. Besides, IMF method has high CR, but the power consumption is higher. For DCA and SCC, CR of the image, *Lily*, could be increased to ~40,000:1, meanwhile the conventional LCD with full-on backlight can only achieve the CR of 1,352. For another pictures, *Robot*, *Strawberry*, and *Sun*, color backlight algorithms not only enhance CR but also reduce power consumption, as shown in Table 4-3 and Fig. 4-14.

4.6 Summary

The indices, image details, power consumption, and contrast ratio, were used to evaluate the image quality by checking the difference between target image and the HDR image obtained by using different backlight algorithms with compensated LC signals. Four test images, *Lily*, *Robot*, *Strawberry*, and *Sun*, with different histogram distributions were chosen for the experiments.

According to those evaluation parameters, two color backlight control algorithms, DCA and SCC, for high dynamic range (HDR) displays were demonstrated for yielding higher performance. From the experimental results, IMF+DCA and SCC in the high CR images not only achieve high contrast ratio (~40,000:1) but also preserve clearer image details. Furthermore, the power consumption could be much lower than full-on backlight. Therefore, the backlight signal can be optimized by the properties of each image by using color backlight algorithms. Consequently, the two color backlight algorithms were successfully applied on a commercial 37" HDR-LCD TV and demonstrated for achieving high image quality and lower power consumption.

Chapter 5

Conclusions & Future Works

5.1 Conclusions

The HDR display is a value-added to LCD TVs, not only reducing the concern of the light leakage of liquid crystals in LCD displays but also yielding the output images to the real world images. Nevertheless, image details have serious distortion when the BL determination method is not applicable.

In this research, the two novel methods of color backlight signal determination for high dynamic range (HDR) displays named “Delta-Color Adjustment (DCA)” and “Segment Color Control (SCC)” were proposed and demonstrated. The DCA method can apply to various backlight algorithms with intensity control because it is based on intensity control to optimize. However, the SCC method can use less steps compared to that of DCA method to get color backlight because it is independent of intensity control. From the experimental results, these two color backlight algorithms in the high CR image not only achieve high contrast ratio (~40,000:1) but also preserve clearer image details. Besides, these two color backlight algorithms can enlarge color gamut of HDR-LCD with color control to 125% NTSC. Finally, the power consumption is also lower than the conventional full-on backlight and intensity controlled backlight. Furthermore, the DCA and SCC methods could optimize by the properties of each image and applied on a commercial 37” HDR-LCD TV of 1920×1080 (HDTV) resolution and with 8×8 local dimming LED(R, G, and B) backlight zones. In conclusion, the DCA and SCC methods can be options for color-backlight HDR-LCD applications to optimize image quality and reduce power consumption.

In the future, HDR-LCDs with color control should be the major trend of high-end LCD TVs due to high image quality and low power consumption.

5.2 Future works

Backlight dimming technology has been adopted by HDR-LCDs for its low power consumption and high contrast ratio. In order to optimize the image quality, the human psychophysics should be considered in HDR-LCDs. Therefore, several issues are listed below.

(a) Quantization Index: The traditional quantization index of image quality was not considered human interest in different images. Therefore, the significant quantization index of image quality was combined color difference (△E) and human interest, as shown in Fig. 5-1. Finally, the backlight algorithm in HDR-LCD could be evaluated by the quantization index.

Fig. 5-1 Significant quantization index of image quality

(b) Color Model: The color model of traditional TVs with full-on backlight has been built. However, the color model of HDR-TV with local dimming could not display correct color yet. Therefore, the next step is to optimize the color model of HDR-TV by considering hardware specification and human interest. Following, the optimized color model will be used to modify the color of HDR display, as shown in Fig. 5-2.

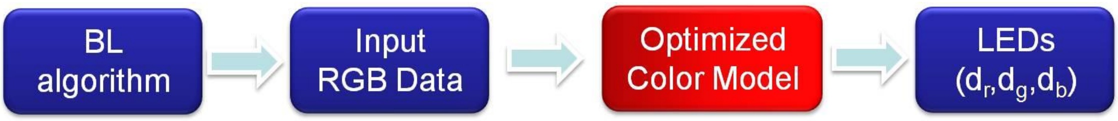


Fig. 5-2 Flow chart of HDR displays by using optimized color model

After setting up the quantization index, the evaluation of HDR-LCD TVs can be more objective. Furthermore, the color of HDR-LCD TVs can also be reproduced correctly by the proposed color model.

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