Concurrent Contrast and Brightness Scaling for a Backlit TFT-LCD Display

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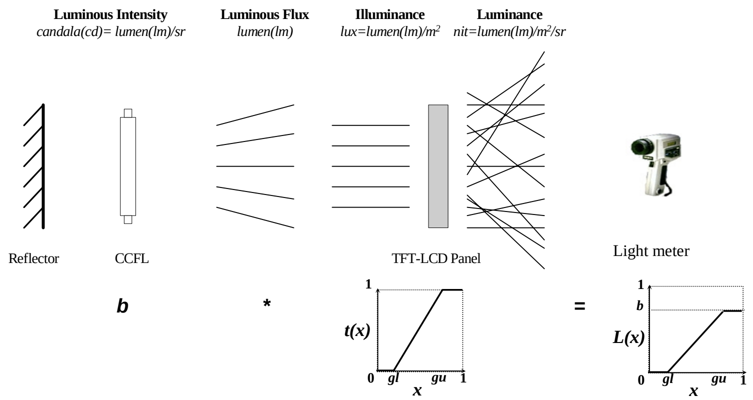
Outline

- Background
- Backlight Scaling and Contrast Fidelity
- Concurrent Brightness and Contrast Scaling
- Experimental Results
- Conclusion

Photometry Terminology and Backlighting

- **Luminous intensity (cd): used to rate a light source**
- **Luminous flux (lm): used to characterize the flux**
- **Illuminance (lux): measured by a light meter**
- **Luminance (nit): used to rate a display**



- **Observed luminance of a pixel value, *x* : *L(x) = b * t(x)***
  - ***b:*** ***backlight luminous intensity (brightness)***
  - ***t(x):*** ***TFT-LCD transmissivity function of pixel value x***

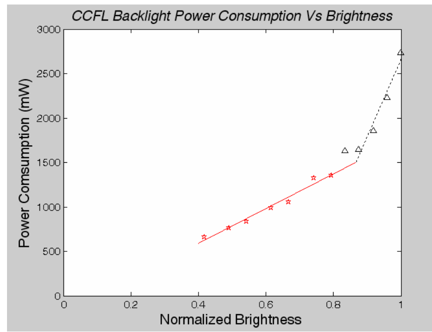
Cold Cathode Fluorescent Lamp

- **CCFL is the most popular backlighting source**
- **Gas discharge phenomenon**
  - **A tube filled with inert gas (argon) and mercury**
  - **High voltage (>500Vrms) ionizes gas**
  - **Current flows through the gas conductor**
  - **Collision of ions generates ultraviolet photons**
  - **UV photons hit phosphor coating and generate visible light**
- **Driver**
  - **CCFL is driven by a DC-AC inverter; Most inverters support dimming control**
  - **High electrical efficiency (> 80%)**
- **Optical efficiency**
  - **Determined by the current, ambient temperature, warm-up time, lamp age, driving waveform, lamp dimension, reflector and diffuser design**
  - **Very low optical efficiency (< 20%)**
- **Saturation phenomenon**
  - **Optical efficiency decreases when driven at >80% of full power**
  - **Because Ionized gas has been fully charged and cannot release more photons**
  - **High temperature and pressure inside the tube also inhibit further discharge**

CCFL Illumination/Power Characterization

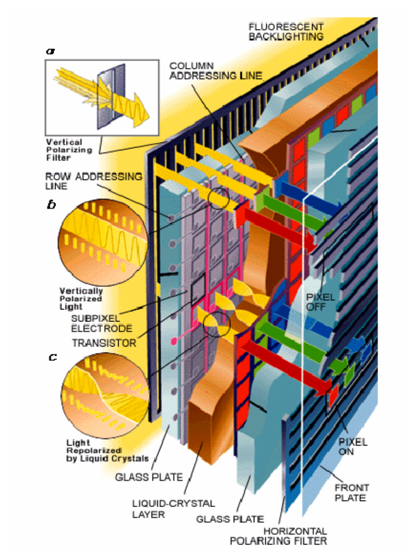
- For the CCFL in LG Philips TFT-LCD LP064V1
- Saturation phenomenon is approximated by using a two-piece linear function
- Operate below 85% power for more economical illumination
- Calibration by using inexpensive light meters
  - Read illuminance
  - Increase pixel value by some fixed increment
  - Decrease backlight brightness until reaching the same illuminance

$$CCFL\_power(b) = \begin{cases} 1952.64 \cdot b - 192.01, & 0 \le b \le 0.8666 \\ 8688.96 \cdot b - 6029.9, & 0.8666 \le b \le 1 \end{cases}$$



Backlit Transmissive LCD

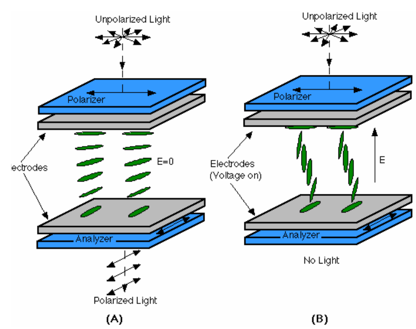
- Liquid Crystals (LC)
  - Small lenses that can change the direction of light wave
- To display a pixel
  - Illuminated by a backlight
  - Vertical polarization
    - Filter out light wave in different directions
  - Control orientation of LCs
    - When electrical field applied
      - Uniform orientation
      - Light passes as is
    - Without an external field
      - Twisted orientation
      - Light is repolarized
  - Horizontal polarization
    - Block the un-twisted light
- Color LCD
  - Mixing R,G, and B sub-pixels
- Grayscale LCD
  - Modulate voltage between the on and off states

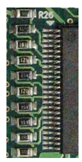


Grayscale Control of TFT-LCD

- Pixel transmissivity (0~255) is controlled by a capacitor that is charged and discharged by a thin-film-transistor (TFT)
- Charge is determined by the voltage driven by the Source Driver
- Source driver requires *k* reference voltages to generate 256 voltage levels
- The *k* reference voltages are generated from a set of voltage dividers
- Resistors $r_1, r_2, \ldots, r_k$ between *Vdd* and *GND*
- The i^{th} output voltage level is*:*

$$V_i = \frac{i}{k} V_{dd}$$





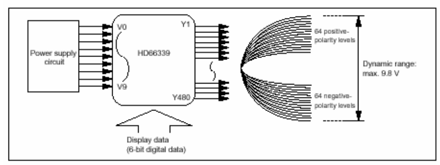
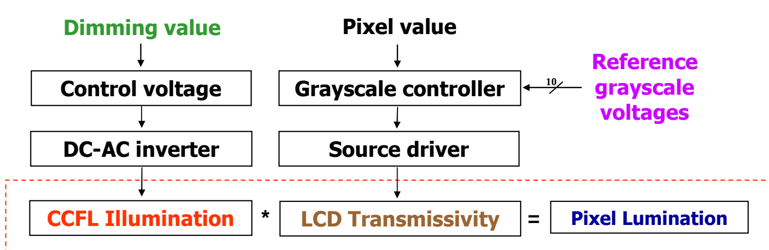


Figure 10 Selection of the LCD Drive Output Level

Backlight Scaling: An Overview



- Backlight Illumination * LCD Transmissivity = Pixel Lumination

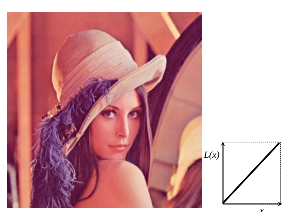
To preserve pixel lumination

- Dim the backlight to reduce power consumption
- Increase LCD transmissivity to preserve the pixel lumination

Brightness and Contrast

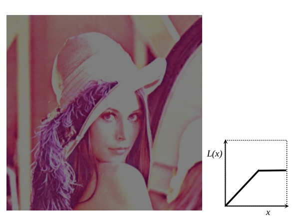
- Why consider contrast
  - Contrast and brightness are correlated. Contrast describes the brightness deviation from the mean.
  - Contrast and brightness controls are present in every CRT or LCD monitor.
  - In the Human Vision System model, vision perception process consists of three stages; Brightness and contrast are involved in the first two stages.
  - Brightness-oriented scaling approaches are too conservative in terms of the power saving.
- Why consider brightness and contrast only
  - Adjusting the backlight and grayscale only changes brightness and contrast; Hue and saturation are not affected.
  - Backlight adjustment affects the whole image. Spatial properties such as sharpness are not affected.

Contrast Scaling Examples

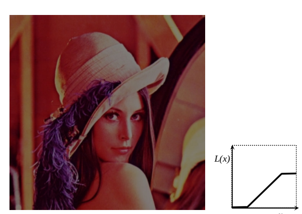


Original image

Dim backlight to 50% without compensation



Brightness-invariant scaling



Optimal contrast -- CBCS

Programmable LCD Reference Driver (PLRD)

- We propose to implement a PLRD to change the transmissivity function t(x) by adjusting the reference voltages
- The PLRD takes two input arguments gl and gu, and then connects nodes 0, …, gl to ground and nodes gu, … ,k to V_k
- The i^{th} output reference voltage is:

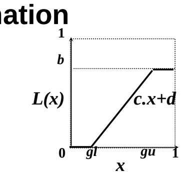
$$V_i' = \begin{cases} V_k & gu \le i \le k \\ \frac{i-gl}{gu-gl} V_k & gl \le i < gu \\ 0 & 0 \le i \le gl \end{cases}$$

- This is a linear transformation function, which can scale brightness and/or contrast
  - Increase brightness
    - ✧ *gu++; gl++;*
  - Increase contrast
    - ✧ *gu--; gl++;*

Contrast Fidelity

- The PLRD performs a linear transformation

$$L(x) = \begin{cases} 0, & 0 \le x \le gl \\ cx+d, & gl \le x \le gu, \\ b, & gu \le x \le 1 \end{cases} \quad where \quad gl = \frac{-d}{c}, \quad gu = \frac{b-d}{c}$$



- Define contrast fidelity function as the derivative of *L(x)*

$$f_c(x) = \begin{cases} 0, & 0 \le x < gl \\ c, & gl \le x \le gu, \quad 0 \le c \le 1 \\ 0, & gu < x \le 1 \end{cases}$$

- *Image histogram (pdf)*

$p(x) \in [0,1],\ x = 0, \ldots, 255$

- *Define the global contrast fidelity function as follows:*

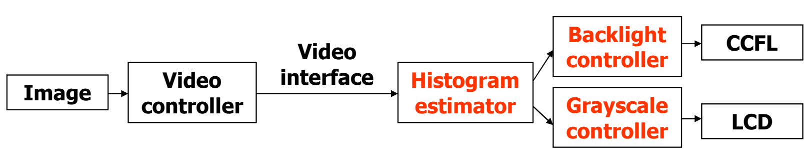
$$F_C = \sum_{gl}^{gu} f_c(x) \cdot p(x).$$

Contrast Fidelity Optimization Problem

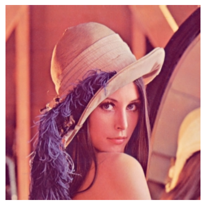
- **Optimal concurrent brightness and contrast scaling policy problem**
  - **Given the image, find the optimal backlight factor and the PLRD transformation function, which maximize the global contrast fidelity**
  - **Three-dimensional solution space: *b, gu,* and *gl***
  - **Problem is too difficult to solve in one-step**
- **Contrast fidelity optimization problem**
  - **Given the image and backlight factor, find the optimal PLRD transformation function that maximizes the global contrast fidelity**
  - **We search for optimal values of *gu* and *gl based on the image histogram data***
  - **Solution space is bounded by *k*, the number of resistors in PLRD; Problem can be solved online**

CBCS Block Diagram

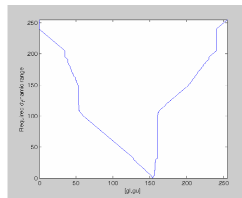
- **CBCS consists of**
  - **Image histogram estimator**
  - **Backlight controller**
  - **Grayscale controller**



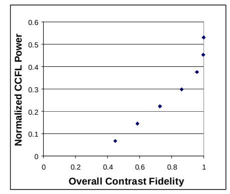
CBCS Optimization Example



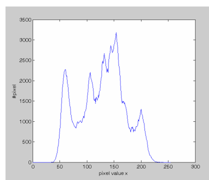
Original



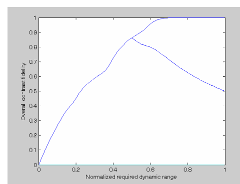
Optimal values of *gl* (left curve) and *gl+dr* (right curve) as functions of dynamic range *dr*



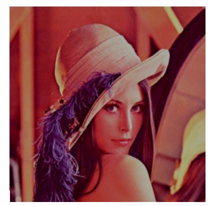
Optimal solutions <F_c,$P_{backlight}$>



Histogram

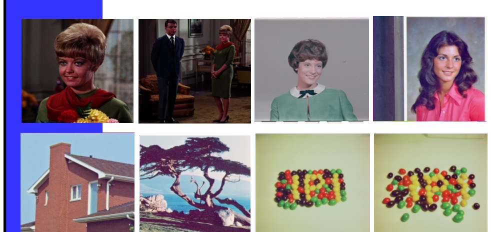


Global contrast fidelity F_c as a function of dynamic range *dr* for *b*=1 (upper curve) and *b*=0.5 (lower curve)



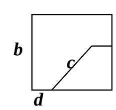
After CBCS with 10% contrast distortion

Experimental Results



- USC SIPI Image Database, Vol. 3 Miscellaneous, 4.1.01~4.1.08
- Size: 256*256
- Color Depth: 24-bit, [0,255] per R, G, B
- TIFF format

Transfer Function



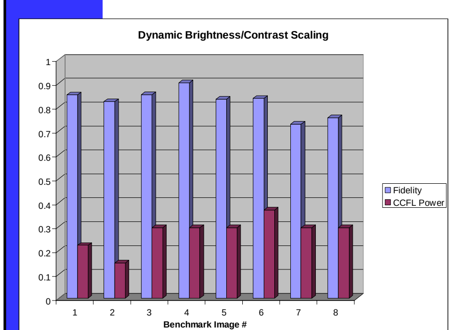
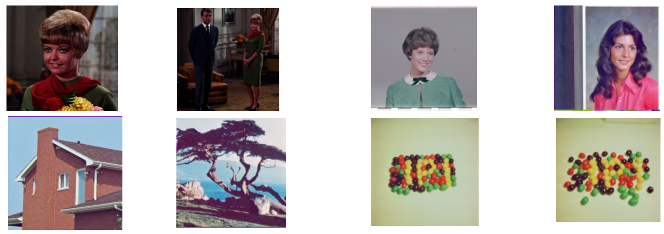


image	b	c	d	Fidelity	CCFL Power	CCFL Power (Normalized	CCFL Power Saving
1	0	1	0	0.8516	589.046	0.2215	0.7785
2	0	1	0	0.8235	393.782	0.1481	0.8519
3	1	1	0.2	0.8528	784.31	0.2950	0.7050
4	1	1	0.2	0.9014	784.31	0.2950	0.7050
5	1	1	0.3	0.833	784.31	0.2950	0.7050
6	1	1	0.2	0.8368	979.574	0.3684	0.6316
7	1	1	0.3	0.729	784.31	0.2950	0.7050
8	1	1	0.3	0.7551	784.31	0.2950	0.7050

Visual Comparison

Before CBCS:



After CBCS:

Conclusion

- Introduced power models for the TFT-LCD panel and the CCFL
- Introduced the notion of contrast fidelity
- Proposed a technique for concurrent brightness and contrast scaling for a CCFL backlit TFT-LCD
- Achieved 3.7X power reduction with a mere 10% contrast distortion

Backup Slides

Previous Work

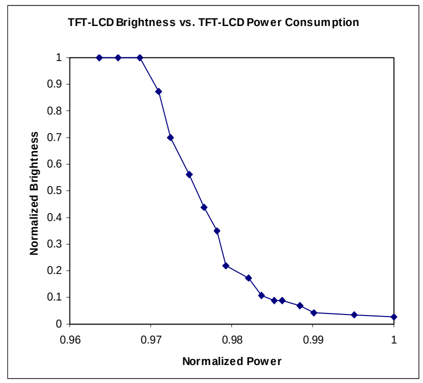
- Backlight Scaling, Choi et al [ISLPED 2002]
  - Dim backlight to save power
  - Increase pixel values to preserve brightness
  - Increase pixel values by + or * in software
  - Implemented in an MPEG2 player
  - Brightness-invariant approach
  - Evaluate quality loss by number of saturated pixels
- Drawbacks
  - Fails to preserve brightness-invariance if scaled by +
  - Lack of consideration of contrast distortion
  - Inaccurate modeling of the CCFL backlight

TFT-LCD Illumination/Power Characterization

- For the LG Philips backlit TFT-LCD Panel LP064V1
- Negative-type TFT-LCD: Power decreases slightly as the transmissivity increases
- Power Characterization
  - Power is modeled by a quadratic function of source-drain voltage
  - High-level brightness is power-free

$$P_{TFT\text{-}LCD}(x)=c_0+c_1x+c_2x^2\ (watts)$$

$$c_0=2.703E\text{-}3,\ c_1=2.821E\text{-}4,\ c_2=2.807E\text{-}5$$



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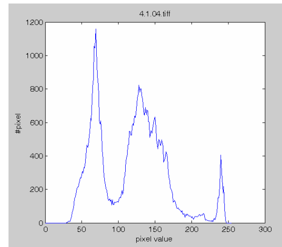
CBCS Optimization Flow

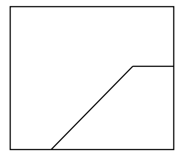
```
CBCS(p[0..255],k) {
  cdf[0]=p[0];
  for (i=0; i<256; i++)
    cdf[i]+=p[i];
  for (b=b_min; b<=b_max; b+=(1/k)) {
    P_b=P_backlight(b);
    for (dr=1; dr<=255; dr+=(256/k)) {
      R_max=-1;
      for (g=0; g<=255-dr; g+=(256/k)) {
        R=cdf[g+dr]-cdf[g];
        if (R>R_max) {
          gl=g;
          R_max=R;
        }
      }
    }
    if (b>=dr)
      F_c=R;
    else
      F_c=(b/dr)*R;
    gu=gl+dr;
    Sol = <F_c,P_b,b,gl,gu>;
    Search solution database for <F_c,*,*,*> and <*,P_b,*,*>;
    if (Sol is not inferior)
      Insert Sol into solution database;
  }
}
```

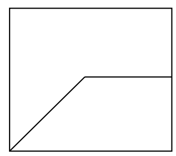
DATE-04

Contrast Fidelity: An Amplifier Analogy

- **Hi-Fi stereo system**
  - Audio amplifier for human ears
  - Fidelity is more important than power for audiophiles
- **LCD display**
  - Video amplifier for human eyes
  - Contrast is more important than brightness for 'videophiles'
- **Dynamic range**
  - Dimming the backlight shrinks the dynamic range
  - We can use the available dynamic range to reproduce the most pixels







Triangular Histogram Estimator

- **Records the following values on the R, G, and B channels**
  - Maximum value
  - Minimum value
  - Moving average
  - Reset these values based on the vertical sync signal (end of frame)
- **Complexity per channel**
  - One register and one comparator to calculate the maximum
  - One register and one comparator to calculate the minimum
  - One register and one adder for calculating the average