ANALYSIS OF THE RESPONSE TIME COMPENSATION SYSTEMS FOR LIQUID CRYSTAL DISPLAYS

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ABSTRACT

Liquid Crystal Displays (LCD) has become a universal choice for television displays in the recent years. Due to the electro-optic nature of the LC materials the response time for gray to gray transitions is not fast enough for high quality video applications. The slow response time of the LCD results in motion artifacts, which are visible as blur of moving objects. In this paper we analyse this non-linear behavior of the LCD and suggest a method to compute the actual acceleration voltage based on the value of the current pixel, motion in the scene and LCD characteristics.

1. INTRODUCTION

Over the last few years, a large number of new display technologies have emerged from the quest for flat, low power and low cost alternative to Cathode Ray Tube(CRT). The desirable features for the new display should include high static resolution, high contrast, high brightness under various lighting condition and excellent dynamic behavior.

Liquid Crystal Display(LCD) has emerged as one of the principal technology to replace CRT as the primary display device. Active-Matrix(AM) LCD technology that enabled the portable computers and thin, flat computer monitors has progressed through various innovations to replace CRT as the display for large screen TV. Television imposes several challenges on the current AMLCD technology that include very large size, dynamic resolution and motion portrayal in the form of faster and uniform response time between gray levels. The frame impulse requirement originates in the difference between how AMLCDs work and the way human visual system (HVS) senses motion from video frames. Each video frame represents a 2D sample of the 3D continuous spectrum sampled at a time instant. These frames when flashed on the retina at a rate faster than the visual system can track, result in continuos motion portrayal. CRTs and Plasma displays approximate this rendering since the luminance from a phosphor pixel decays away rapidly. The LCDs pixel's luminance, however remains approximately constant over the entire frame. Fig.1 shows measured data of a CRT pixel's luminance profile. For an equivalently bright LCD, the LCD pixel would be the luminance of the average luminance shown in Fig.1. Since LCDs are progressively scanned, at every time instant there is a partial frame of both previous and current frame visible on the screen with a progressively moving tear boundary through it. The scan and hold aspect of the LCD is nearly ideal for the static image content but is undesirable from the stand point of video display.

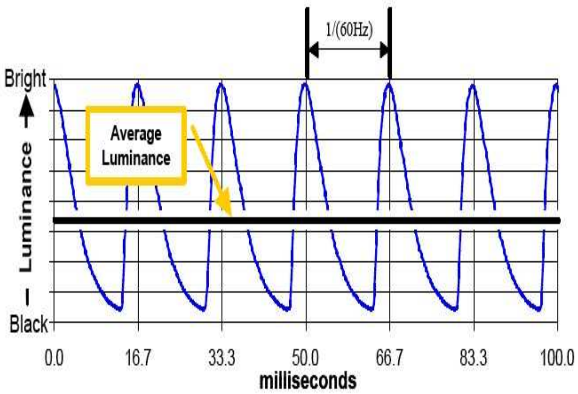

Figure 1: Luminance profile of a typical CRT pixel, reproduced under permission from Richard McCartney

Until recently, it wasn't widely appreciated that in general, the response times of the commercially available LCD panels are inadequate to show high quality video. Furthermore, the LCD industry specifications report only the off-to-on response times of the panel. This is the fastest response time mode of the panel. Representative response time of 15-20 ms would be adequate if all gray to gray transitions were at this rate. However gray to gray response times can be many times longer, typically in the order of hundreds of milliseconds. This accounts for the poor quality of the motion portrayal on the LCD panels.

A lot of effort has been put into speeding up the response of the LCD panels. The most popular method to improve the response speed of the LCD pixels is based on "overdriving". However, speeding up the response of LC materials to lower values is not enough to completely avoid motion blur [1]. This is caused by the active matrix principle itself, which exhibits a sample-and-hold characteristic, causing light emission during the whole frame time. An "inverse filtering" has been proposed in [2] that can reduce motion blur on LCDs. However the inherent assumption that the aperture function of the display is linear and can be put in anywhere in the video processing stages is not valid. The output of the response time compensation (RTC) block is tied directly to the non-linear panel characteristic, thus placing the compensation block upstream of any image processing block is flawed.

In this paper we will analyze the reason for the slow response time of the LCD panels and how the response time compensation circuits work to improve the response time of the panel. We will proposed a method to compute the over and under boost values that exit the RTC block, that actually represent the appropriate voltages that provides the right boost for a target display. The paper is organized as follows:

1. The LCD response time theory is explained in section 2
2. Section 3 describes the display flow of a television system and why RTC is necessary
3. Section 4 analyzes the theory behind RTC

2. RESPONSE TIME THEORY

The transition time between any two gray levels in a LCD depends on various factors that can be divided in two major classes [3].

- Factors related to the forcing torque, i.e the torque required to move the LC molecules.
- Factors related to the resistance to the torque, i.e the flow dynamics, viscosity etc.

The second factor is intrinsic to the LC materials and cannot be changed externally. Thus the factor that can directly result in a faster or slower response is the forcing torque of the LC materials.

The forcing torque of the LC molecules is a resultant of two torques in the system. The excitation torque that is induced by an electric field and a restoring torque induced by the spring constants. The response time required to move the molecules from one orientation to another is dependent on both factors. Thus it can be deduced from the present state of the crystalline deformation, direction and magnitude of the torque.

The induced torque on the LC molecules depend on the square of the electric field [3].

$$T = \frac{1}{2}(\varepsilon_{parallel} - \varepsilon_{perpendicular})\varepsilon_0 V^2 \sin(2\theta)$$

where ε_x are the different dielectric constants, V is the applied voltage.

While the torque is instantaneous with the electric field, the resulting molecular movement and the associated optical response lags behind. *When the applied torque in the current frame is higher than the applied torque in the previous frame, the response time varies roughly inversely with the square of the applied voltage* mitigated by the mostly non-linear factors related to the resistance to movement. *When the applied torque in the current frame is lower than the applied torque of the previous frame, the response time varies roughly inversely linearly with the applied voltage*, depending largely on the passive, non-linear factors trying to establish long-range, nematic order consistent with the wall orientation.

Since there are two mechanisms at work, there are two compensation strategies to accelerate the transition. For this reason, Response Time Compensation (RTC) rather than over-drive method is preferred because half of the time the applied compensation is to overdrive the display and half of the time it is to under-drive the display depending on the direction of the transition. The mechanism to implement these strategies, however, is the same in both directions of compensation. Fig.2 illustrates the application of the compensation values.

3. DISPLAY FLOW IN TV

The aim of a display system is to faithfully reconstruct the physical light emissions, corresponding to the original image, at the correct position and time. The characteristics of this reconstruction process when combined with characteristics of the human visual system, has explained many artifacts in the literature. The blurring effect due to the sample and hold characteristics of LCDs are explained in [4] and [2].

The very basic representation of the display chain and the analysis of the intermediate steps can be found in [2]. The image as produced by the display is given by

$$I_{disp}(x,y,t) \quad = \quad I_s(x,y,t) * A(x,y,t) \qquad (1)$$

where $I_s(x,y,t)$ is the discrete time sampled video spectrum and $A(x,y,t)$ is the display aperture also known as reconstruction or point spread function.

For Sample and hold type display is assumed to have a constant light emission during the whole frame period. This behavior results in a typical "boxcar" reconstruction function with a width equal to the hold time T_h. However, typically LCDs do not behave like that. The LCD behaves like a first order system when it changes from one gray level to another. This non-linearity is a function of current and previous gray level, and the threshold and saturation voltage of the LCD. Thus a simple frequency domain representation in the form of *sinc* function is not possible.

It is true that sample and hold behavior of the LCD results in a better display than an impulse display for static image due to the absence of wide area flicker. But in case of motion the performance degrades significantly. If we assume a translational model for motion then

$$I_m(x,y,t+\delta t) \quad = \quad I_s(x - d_x\delta t, y - d_y\delta t, t)$$

where $s_x = d_x\delta t$ and $s_y = d_y\delta t$ are the displacements in the time instant. The moving image is then sampled and reconstructed in the display chain, after which it reaches the eye. The eye tracking performs the motion compensation on the reconstructed output of the display. It is explained in [2], how the sample and hold light emission of LCD coupled with eye tracking causes the motion blur in the final output. A motion compensated sharpening is suggested to improve the performance. The problem typically associated with the motion compensated inverse filtering is it boosts noise in the flat region and depends on "true" motion in the scene. Also when the reconstruction filter is non-linear a simple inverse filtering may not be adequate.

In this paper we will analyze how the knowledge of the motion along with the non-linear characteristic of the LC materials helps in compensating for this artifact. It is assumed

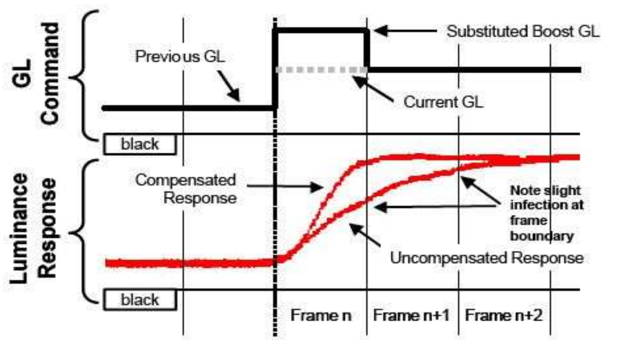

Figure 2: Response time compensation mechanism

that $I_0(x,y,t)$ is the intensity of the pixel at time t and after time T it changes to $I_{FINAL}(x,y,t+T)$, where T is the refresh period of the display. If we assume that the change in the pixel intensity is solely due to motion in the scene then

$$I_{FINAL}(x,y,t+T) \quad = \quad I_0(x-d_xT,y-d_yT,t) \qquad (2)$$

Now due to characteristics of the LC materials as explained in Sec.2, it is often not possible to reach the desired pixel intensity of $I_{FINAL}(x,y,t)$ in the given time. The RTC system over or under boosts the pixel based on the previous and current gray level. If the "true" motion present in the scene is known, then the over and under boost value can be precomputed as per the design methodology described in Sec. 4. Thus the simple inverse filtering can be replaced by the motion compensated non-linear filtering. As the inherent nonlinearity of the LC material is built into the design, this block can only be placed after all the other image processing block.

4. ANALYSIS OF RTC

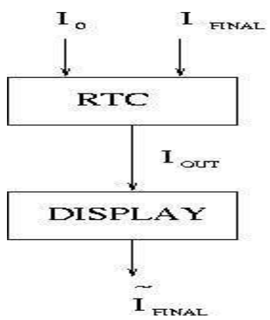

Figure 3: Block diagram of a system with RTC and display. Given an initial intensity I_0 and desired final intesity I_{FINAL} after prespecified time interval, RTC block precompensates for the LCD characteristics and outputs I_{OUT} which acts as input to the display. Actual output intensity of the display after prespecified time interval is $\tilde{I}_{FINAL}$ which should be as close to I_{FINAL} as possible.

Let output intensity of LCD at any time instant be I_0 as shown in Figure 3. Further, let input signal changes to a value corresponding to steady state output of I_{out}. Response characteristics of display will not allow the output to immediately change. Let us assume that response characteristics is governed by following first order differential equation,

$$\tau \frac{dI}{dt} = I_{out} - I \qquad (3)$$

with initial condition $I|_{t=0} = I_0$, where τ is response time constant. Solution is given by,

$$I(t) = I_{out} - (I_{out} - I_0)\exp\left(-\frac{t}{\tau}\right) \qquad (4)$$

But, as reported in previous section, response characteristics of LCD exhibits anisotropic behaviour. In particular, for increasing intensity responce time is proportional to reciprocal of square of applied voltage, while for decreasing intensity it is proportional to reciprocal of applied voltage. Although, change of capacitance with LC orientation also plays a part in the anisotropic behaviour of response characteristics, in this analysis we don't take into account the capacitive effects. Considering the anisotropic nature of response, (4) gives

$$\begin{array}{ll} \tau_1 = \frac{k_1}{V^2} & \text{If } I_{out} > I_0 \\ \tau_2 = \frac{k_2}{V} & \text{If } I_{out} < I_0 \end{array} \qquad (5)$$

where, k_1 and k_2 are constants and V is applied voltage. Substituting the values of τ from (5) into (4), we get

$$\begin{array}{ll} I(t) = I_{out} - (I_{out} - I_0)\exp\left(-\frac{t}{k_1}v^2\right) & \text{If } I_{out} > I_0 \\ I(t) = I_{out} - (I_{out} - I_0)\exp\left(-\frac{t}{k_2}v\right) & \text{If } I_{out} < I_0 \end{array} \qquad (6)$$

Although, the output intensity will in principle assymptotically converge to desired intensity, in practice allowed convergence time T is restricted by refresh rate of the display (e.g. 16ms for 60Hz). Hence, the final intensity achieved is given by

$$\begin{array}{ll} \tilde{I}_{final} = I_{out} - (I_{out} - I_0)\exp\left(-\frac{T}{k_1}v^2\right) & \text{If } I_{out} > I_0 \\ \tilde{I}_{final} = I_{out} - (I_{out} - I_0)\exp\left(-\frac{T}{k_2}v\right) & \text{If } I_{out} < I_0 \end{array} \qquad (7)$$

Since, applied voltage V corresponds to intended intensity

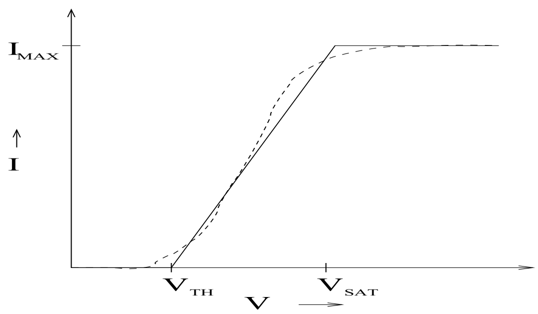

Figure 4: S-shaped intensity-voltage characteristics of LCD and its piecewise linear approximation

I_{out}, according to linearized approximation of 'S' shaped 'voltage-intensity' characteristics of LCD as shown is Figure 4, it is given by

$$\begin{array}{ll} V \leq V_{th} & I \leq 0 \\ V \geq V_{sat} & I \geq I_{max} \\ V = kI + V_{th} & otherwise \end{array} \qquad (8)$$

where, V_{th} and V_{sat} are threshold and saturation voltages respectively. I_{max} is maximum display intensity and k is constant. Restricting our attention to linear region (since it covers all intermediate intensity range) and substituting corresponding expression for V is (7), we get

$$\begin{array}{l} \text{If } I_{out} > I_0 \\ \tilde{I}_{final} = I_{out} - (I_{out} - I_0)\exp\left(-\frac{T}{k_1}(kI_{out} + V_{th})^2\right) \\ \text{If } I_{out} < I_0 \\ \tilde{I}_{final} = I_{out} - (I_{out} - I_0)\exp\left(-\frac{T}{k_2}(kI_{out} + V_{th})\right) \end{array} \qquad (9)$$

Let, intended otuput of overall system be I_{final}, but in order to precompensate for the response characteristics of LCD, a video processing unit outputs I_{out}. We wish to find the mapping from T_{final} to I_{out}. Equating the actual output of the system $\tilde{I}_{final}$ with intended output I_{final} we get,

$$\begin{array}{l}\text{If } I_{out} > I_0 \\ I_{final} = I_{out} - (I_{out} - I_0)\exp(-\frac{T}{k_1}(kI_{out} + V_{th})^2) \\ \text{If } I_{out} < I_0 \\ I_{final} = I_{out} - (I_{out} - I_0)\exp(-\frac{T}{k_2}(kI_{out} + V_{th}))\end{array} \quad (10)$$

Considering the transcendental nature of (10) it is difficult to find analytic expression for I_{out} as a function of I_{final}. We consider two different subcases $kI_{out} \ll V_{th}$ and $kI_{out} \gg V_{th}$.

4.1 Case I

$I_{out} > I_0$ and $kI_{out} \ll V_{th}$

$$I_{final} \simeq I_{out} - (I_{out} - I_0)\exp(-\frac{T}{k_1}V_{th}^2) \quad (11)$$
$$= I_{out} - c_1(I_{out} - I_0) \quad (12)$$
$$\Rightarrow I_{out} = \frac{I_{final} - c_1 I_0}{(1 - c_1)} \quad (13)$$

where, $c_1 = \exp(-\frac{T}{k_1}V_{th}^2)$ is another constant.

4.2 Case II

$I_{out} > I_0$ and $kI_{out} \gg V_{th}$

$$I_{final} \simeq I_{out} - (I_{out} - I_0)\exp(-\frac{T}{k_1}k^2 I_{out}^2) \quad (14)$$
$$= I_{out} - (I_{out} - I_0)(1 - \frac{T}{k_1}k^2 I_{out}^2 + \text{h.o.t.}) \quad (15)$$

Assuming higher order terms are small enough to be neglected,

$$I_0 + \frac{T}{k_1}I_{out}^3 - \frac{T}{k_1}I_0 I_{out}^2 \simeq I_{final} \quad (16)$$
$$\Rightarrow aI_{out}^3 + bI_{out}^2 + c = 0 \quad (17)$$

where, $a = \frac{T}{k_1}$, $b = -\frac{T}{k_1}I_0$ and $c = I_0 - I_{final}$. (17), being a simple cubic equation, permits analytical expression for solution. One real solution is given by,

$$I_{out} = x + \frac{1}{9}\frac{b^2}{a^2 x} - \frac{1}{3}\frac{b}{a} \quad (18)$$
$$x^3 = -\frac{1}{54}\frac{27a^2c - 2b^3}{a^3} + \frac{1}{18}\frac{\sqrt{3}\sqrt{27a^2c^2 + 4bc^3}}{a^2} \quad (19)$$

4.3 Case III

$I_{out} < I_0$ and $kI_{out} \gg V_{th}$

$$I_{final} \simeq I_{out} - (I_{out} - I_0)\exp(-\frac{T}{k_2}V_{th}) \quad (20)$$
$$= I_{out} - c_2(I_{out} - I_0) \quad (21)$$
$$\Rightarrow I_{out} = \frac{I_{final} - c_2 I_0}{(1 - c_2)}$$

where, $c_2 = \exp(-\frac{T}{k_2}V_{th})$ is another constant. Result in (22) and (13) has a simple geometric interpretation as shown in Figure 5.

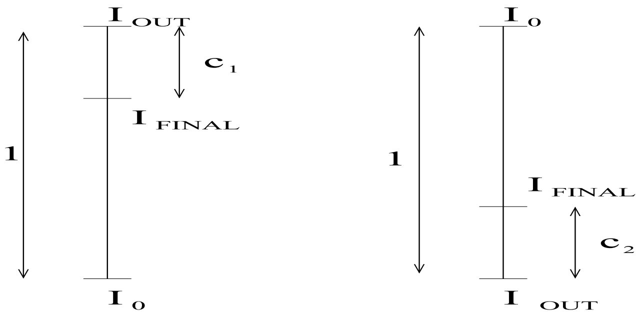

Figure 5: Interpretation of result for case I and case III. When desired intensity is larger than current intensity, overdrive is needed and when desired intensity is smaller than current intensity, underdrive is needed. Distances shown in the figure are only relative and not absolute.

4.4 Case IV

$I_{out} < I_0$ and $kI_{out} \ll V_{th}$

$$I_{final} \simeq I_{out} - (I_{out} - I_0)\exp(-\frac{T}{k_2}kI_{out}) \quad (22)$$
$$= I_{out} - (I_{out} - I_0)(1 - \frac{T}{k_2}kI_{out} + h.o.t.) \quad (23)$$

Ignoring the higher order terms.

$$I_0 + \frac{T}{k_2}kI_{out}^2 - \frac{T}{k_2}kI_0 I_{out} = I_{final} \quad (24)$$
$$\Rightarrow aI_{out}^2 + bI_{out} + c = 0 \quad (25)$$

where, $a = \frac{T}{k_2}k$, $b = -\frac{T}{k_2}kI_0$, $c = I_0 - I_{final}$. (25) can be easily solved and one solution can be chosen which is consistent with the assumptions.

5. CONCLUSION

In this paper, we proposed an LCD RTC framework based on theoretical analysis of the effect of non-ideal display characteristics. Associated processing can be combined with other image processing operations, thus obviating the need to commit hardware resources for RTC in LCD timing controller circuits. Present work can be extended to incorporate the motion compensated filtering, as well as other processing that directly changes the pixel intensities such as contrast or saturation enhancement.

REFERENCES

[1] T. Kurita, "Moving picture quality improvement for hold-type am-lcds," *SID Digest*, pp. 986–989, May 2001.

[2] M A. Klompenhouwer and L Velthoven, "Motion blur reduction for liquid crystal displays: Motion compensated inverse filtering," *Proc of SPIE-IS&T*, , no. 2, pp. 690–699, 2004.

[3] R I. McCartney, "A liquid crystal display response time compensation feature integrated into an lcd panel timing controller," *SID Diegst*, vol. 3, pp. 1350–1353, 2004.

[4] G de Haan and M A. Klompenhouwer, "An overview of flaws in emerging television displays and remedial video processing," *IEEE Trans on Consumer Elect*, vol. 47, no. 3, August 2001.