A Liquid Crystal Display Response Time Compensation Feature Integrated into an LCD Panel Timing Controller

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48.3: A Liquid Crystal Display Response Time Compensation Feature Integrated into an LCD Panel Timing Controller

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Abstract

The electro-optic response times of the principal LCD modes are not fast enough for video applications. Applying a one-frame acceleration voltage, in lieu of the correct video command, can compensate the slow response time. This paper discusses the operation and design choices of a timing controller with an embedded LCD response time compensator (RTC).

1. Background and History

Active-matrix LCD technology which enabled the Notebook PC and the thin, flat computer Monitor through a progression of technological innovations now ready to take on television. Television imposes several new challenges on the current AMLCD art including: a broader color envelope, very large sizes, image frame impulsing and faster, more uniform response time between gray levels. The broader color envelope originates in video standards. AMLCD NBPCs and monitor applications have actually taken liberties to reduce the color envelope as a method to improve transmissivity and thereby reduce backlight power and gain other benefits. A number of methods are being developed to improve the color envelope while still maintaining high transmissivity.

Targeted LCD-TV screen sizes range from 15 inches through greater than 50 inches. Acknowledging some overlap, these sizes are substantially larger than desktop monitor applications. Generation 5, 6 and 7 factories are being brought on-line to support these new sizes.

The frame impulse requirement originates in the difference between how AMLCDs operate and the way that the human visual system senses motion from changing still frames. Each still frame represents a sample of the image frozen at an instant in time. When these still frames are flashed momentarily on the retina at rates faster than the visual system can track, the frames fuse into continuous motion. Film projectors at theaters approximate this impulse rendering. CRTs and Plasma displays approximate this rendering as well since the luminance from a phosphor pixel decays away rapidly. Figure 1 shows measured data of a CRT pixel's luminance profile.

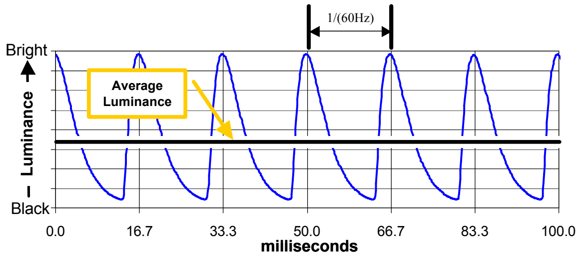

Figure 1. *The luminance profile in time of a typical CRT pixel*

The AMLCD pixel's luminance, however, is virtually constant over the entire frame. For an equivalently bright LCD, the LCD pixel would be the luminance of the average luminance shown in Figure 1. Since LCDs are progressively scanned, at every instant there is a partial frame of both the old and the new frame visible on the screen with a progressively moving tear boundary through it. This scan-and-hold aspect of the LCD is nearly ideal for presentation of static images such as computer-generated spreadsheets and word documents where flicker is minimal compared with CRTs, but it is undesirable from the standpoint of video applications. Uniform gray-to-gray response times coupled with mechanisms to modulate the backlight are among the expected solutions to meet the impulse requirements for video applications.

Until recently, it wasn't widely appreciated that in general, the response times of the commercially important LCD modes, in particular TN, IPS and MVA, are inadequate to show high quality video[1]. This is due to several factors including that computer applications typically have very low video content and what little video content there is tends to be poor quality (e.g. internet video streams, file based video clips and game graphics). Furthermore, the LCD industry specifications report only the off-to-on response times of the panel. This is the fastest response mode of the liquid crystal. Response times of 15 to 25 milliseconds is representative and would be adequate if all gray-to-gray transitions were at this rate. However, the gray-to-gray response times can be many times longer, i.e. hundreds of milliseconds. These gray-to-gray transitions account for the poor quality of motion video when it is due the LCD response time.

1.1 LCD Response Time Theory

The transition time between any two gray levels in a nematic LCD depends on several factors which can be divided into two classes, factors related to the forcing torque, i.e. the torque attempting to move the molecules, and factors related to the resistance to movement such as flow dynamics, viscosity etc. The forces related to the resistance to movement are intrinsic to the LC material and its environment such as pre-tilt, cell thickness, temperature, director orientation distribution, etc.

The forcing torque lies in the balance of two torques, the exciting torque that is induced by an electric field and a restoring torque induced by the spring constants working to establish long-range nematic order[2]. The response time required to move the molecules from one orientation to another is dependent on both factors which can be deduced from knowledge of the present state of the crystalline deformation and whether the movement is due to an increase or a decrease in the torque from the electric field.

The induced torque on the LC molecule depends on the square of the electric field…

$$T = \tfrac{1}{2}\,(\varepsilon_{\text{parallel}} - \varepsilon_{\text{perpendicular}})\,\varepsilon_o\,E^2 \sin(2\theta)$$

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[1] OCB mode is adequately fast but isn't mainstream in it's application.

[2] Each of the three modes discussed, Twisted Nematic (TN), IPS and MVA are nematic modes.

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The induced torque is therefore independent of the polarity of the electric field and increases with the square of 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 we prefer the more generic term, Response Time Compensation (RTC) rather than over-drive method 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.

Figure 2 illustrates a simple block diagram of the RTC mechanism common to all the recently announced "over-drive" methods.[1,2,3,4,5] The basic theory of operation is that the RTC block intercepts the digital video stream and compares the previous gray level command to each pixel with the current gray level command and chooses a pre-determined alternate gray level from a look-up table (LUT). Since every combination of previous and current commands is accounted for in the LUT, booth directions of compensation (over- and under-boost) are provided.

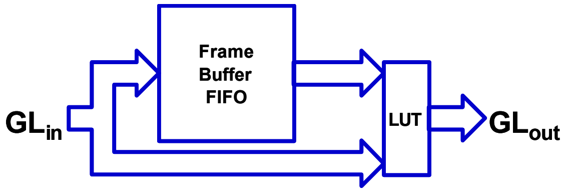

Figure 2. *Block Diagram of RTC Mechanism*

Figures 3 and 4 illustrate the application of the compensation value. When the LUT determines that the previous and current gray levels are different, it outputs the pre-determined compensation value experimentally chosen to just bring the brightness to the target value at the end of one frame. The significance of stressing that the underlying mechanisms of rise and fall times are different is that the excitation time is bounded only by the driver voltage whereas it is impossible to remove more than all the electric field in order to compensate the relaxation transition. This means that, in the relaxation case, the response time of the liquid crystal is dependent only on internal forcing factors and flow constraints rather than externally applied fields. However, there is value to compensating the relaxation direction for reasons related more to the active matrix than to the relaxation mechanism.

The active matrix plays an import and not widely recognized role in the response time of the AMLCD. In the active matrix, a voltage is applied across the liquid crystal, which electrically is a parallel plate capacitor with the liquid crystal being the dielectric. In time, as the liquid crystal's structure begins to deform in response to the electric field (i.e. the voltage stored across the capacitor), the capacitance itself changes. This capacitance change is due to the dielectric anisotropy in which the LC molecules exhibit different dielectric constants depending on their orientation to the electric field. Since during this transition time the TFT switch is open, no charge can flow into or out of the LC capacitor. The charge in the LC capacitor must be conserved, in other words…

$$\textit{Since}\ \mathbf{Q = CV} \quad \textit{Then…} \quad \mathbf{C_o V_o = C_f V_f}$$

Therefore, if an initial voltage (V_o) is applied across the LC capacitor (C_o) that causes it in time, to reduce the capacitance (a decreased electric field) ($C_f < C_o$), the voltage across the capacitor will necessarily rise ($V_f > V_o$). If an initial voltage (V_o) is applied across the LC capacitor (C_o) that causes it in time, to increase the capacitance (an increased electric field) ($C_f > C_o$), the voltage across the capacitor will necessarily fall ($V_f < V_o$). Figures 5 and 6 illustrate this behavior for the relaxation. Figure 3 illustrates the effect for the filed induced case.

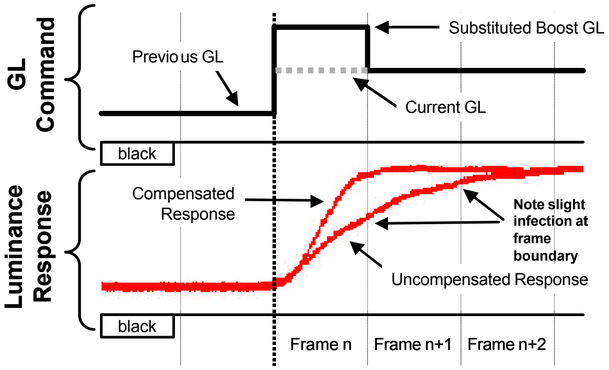

Figure 3. *Illustration of Field Induced RTC Mechanism*

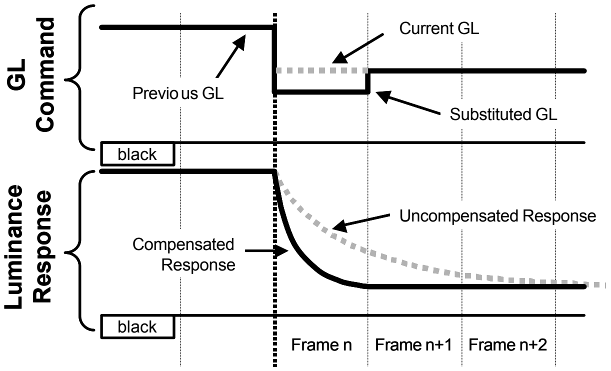

Figure 4. *Illustration of Relaxation Induced RTC Mechanism*

The RTC method of using a frame FIFO and a LUT to accelerate the response of the LCD is not new.[6,7,8,9] It was used for example by the author to improve the image quality of fast moving graphical symbols of LCD based flight instruments circa 1992. RTC has been in production on the flight instruments of the Boeing 777 airplane, versions of the Boeing 737, the Space Shuttle and other aircraft for many years. What is new is the application of RTC to consumer applications and the attendant cost-benefit compromises.

The emerging need for RTC in the consumer market today really arises from two facts. First, that most wide viewing angle technologies, including IPS and MVA, have intrinsically slower response times than even TN. And second, these wide viewing angle technologies are essential for the large-area TV market. Some of the cost-performance considerations we made in the design of our timing controller chip are reported on in this paper.

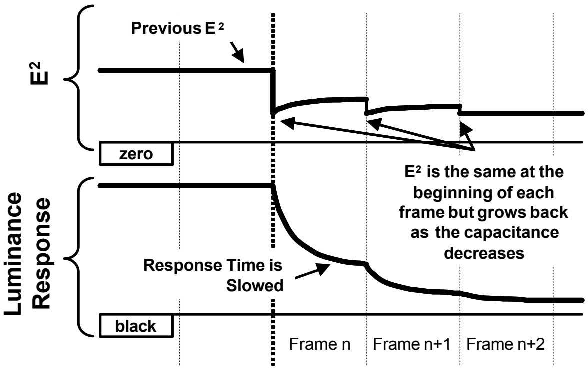

Figure 5. *Illustration of Dynamic Capacitance Effect*

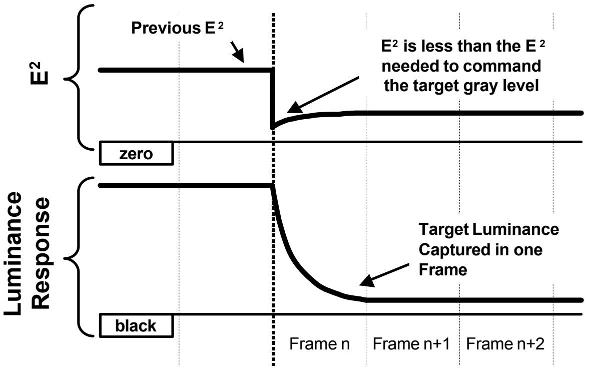

Figure 6. *RTC Mechanism to Compensate Dynamic Capacitance*

2. System Design

Functionally, the RTC block can reside anywhere in the digital video stream. However, since the output of the block is tied directly to a non-linear panel characteristic, placing the RTC block upstream of any image-processing block is flawed. In other words, the over- or under-boost values that exit the RTC block are coded in grayscale, but really represent the appropriate voltages that just provide the right boost for a the target gray level command. Any digital scaling of brightness following the RTC block would produce erroneous results during transitions. Likewise, any scaling of voltages in the column driver following the determination of the LUT contents would be flawed.

Therefore, the most reasonable location for the RTC block in the system is as the last stage of the timing controller. Not only is it safe from downstream image processing manipulation but also, it keeps the display panel and the LUT that characterizes it in the same module. This coupling assures that input data is independent of the module supplier. Figure 7 shows the system block diagram.

2.1 RTC Function Design

As the current gray level commands arrive, the RTC logic retrieves the previous gray level to that same element from an external full frame FIFO memory. Simultaneously, it stores the current gray level in the FIFO memory for use in the next frame. The external FIFO is an SDRAM that is controlled by the RTC logic of TCON to operate it as a FIFO memory. The RTC controller then compares the two commands (current and previous) for each red, green and blue element using separate RGB look-up tables (LUTs). The contents of the LUT provide a unique gray level surrogate for each pairing possibility of current and previous commands. For ease of development the contents of the LUTs are provided either from an internal ROM (production) or if present, an external EEPROM (development). We also created calibration software and processes, which allow the developer to determine the custom values for each LUT.

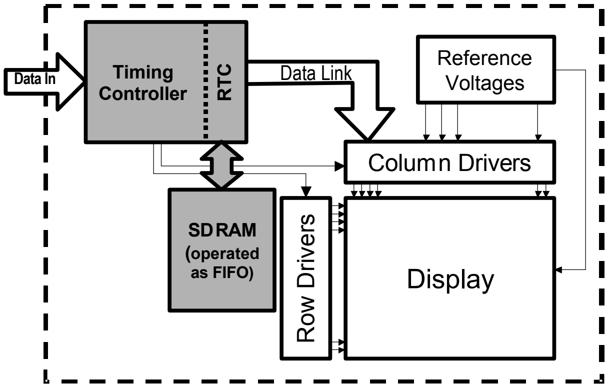

Figure 7. *Block Diagram of the Display Module with RTC*

Ideally, there would be a LUT entry for each combination of previous and current gray levels but this would require a large LUT, 256x256x8 bits for each color. We can get virtually all of the information in that 256x256 table from a much smaller 17x17 table through bi-linearly interpolating between major values.

		Previous GL																
		0	**16**	**32**	**48**	**64**	**80**	**96**	**112**	**128**	**144**	**160**	**176**	**192**	**208**	**224**	**240**	**256**
Current GL	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	16	27	16	8	4	3	4	4	0	0	0	0	0	0	0	0	0	0
	32	52	45	32	20	16	17	16	5	4	4	0	0	0	0	0	0	0
	48	77	64	61	48	36	33	35	15	15	16	4	4	0	0	0	0	0
	64	96	80	80	75	64	52	60	35	31	32	16	16	4	3	0	0	0
	80	116	99	101	100	93	80	79	60	51	49	31	37	16	17	4	0	0
	96	140	125	124	128	116	109	96	83	77	67	52	61	31	31	17	0	0
	112	164	143	147	155	140	131	124	112	101	92	81	84	51	52	33	8	0
	128	188	160	168	180	163	160	144	143	128	116	108	108	80	76	52	28	4
	144	208	183	187	209	191	187	164	176	159	144	132	132	108	99	80	53	17
	160	224	216	216	236	220	213	189	204	192	176	160	155	131	128	108	75	32
	176	241	241	240	251	236	232	212	223	220	207	192	176	159	155	132	101	47
	192	251	251	251	255	244	245	235	239	236	233	217	209	192	181	157	127	65
	208	255	255	255	255	250	251	251	252	244	244	232	236	220	208	185	159	84
	224	255	255	255	255	255	255	255	255	252	251	248	252	241	236	224	196	115
	240	255	255	255	255	255	255	255	255	255	255	255	255	250	250	247	240	173
	256	256	256	256	256	256	256	256	256	256	256	256	256	256	256	256	256	256

Figure 8. *Example of bilinear LUT entries to interpolate the previous gray level of 94 and the current gray level of 165*

Bi-linear interpolation requires four entries from the table, the values from the closest value below and above both the previous and current gray level. For example, if the previous gray level is 94 we can find the major values in the table by recognizing that 94 lies between 80 and 96. Similarly, if the current gray level is 165 then 160 and 176 are the next lower and next higher major current gray levels. Figure 8 illustrates that for this example, we can extract 4 values from the table, namely 213 at (80,160), 189 at (96,160), 232 at (80,176) and 212 at (96,176). From these four numbers we can interpolate to find a single number that best approximates the value for the original pairing of 94 previous GL and 165 current GL.

The contents typical of the LUT are shown graphically in Figure 9. This family of curves shows the output ("boost") gray level as a function of current gray level. Each of the 17 curves represents a different starting or *previous* gray level. This graph shows the legitimacy of interpolation (i.e. the curves are smooth and well behaved). Note that without boost (i.e. the LCD responded fast enough), all the curves would fall on the diagonal line running from bottom left to upper right. The asymmetry of the data around the diagonal centerline in this graph is a manifestation of the two different mechanisms behind the rise and fall times.

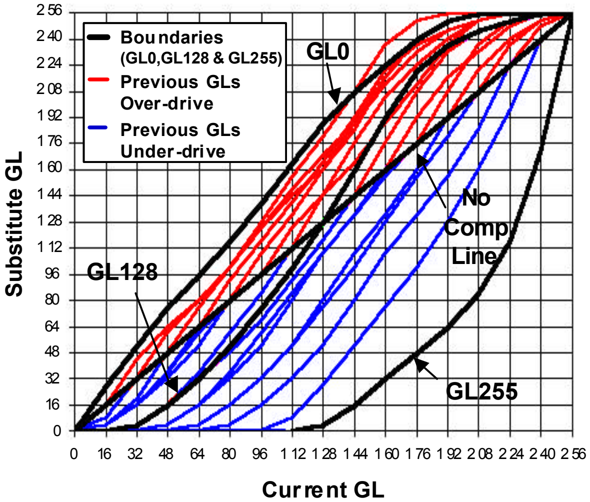

Figure 9. *Example of bilinear LUT entries to interpolate the previous gray level of 94 and the current gray level of 165.*

Note the saturation along the bottom of the curve space. This means that when the previous GL is 255 and the current gray level is anything less than GL112, GL0 will be applied. This implies that for this liquid crystal, going from full bright (255) to half bright or less (<128) requires maximum under-drive in order to maximize the response time.

Storing less than the full 8-bits of the previous gray level can minimize the external SDRAM size with minimal impact on image quality. Since external SDRAMs come in increments of 16-bit wide interfaces, truncating a 24-bit pixel to 16-bits is beneficial. These 16 bits could be allocated as 5-bits of each color, RGB with one unused. The implication of this truncation compression is that the previous gray level is known with less precision. In other words, truncating the lower 3 bits of the previous GL means that the previous GL is quantified into 32 zones. The loss of precision means that there will be some variability in the gray-to-gray transition time. However, this variability is quite small compared with the uncompensated variability and represents a very good cost-performance trade-off.

This 5R-5G-5B truncation is one of 4 different truncation options provided in the design. Among the other choices is the 5R-6G-5B option that uses all 16 SDRAM bits and provides better precision to the green channel where human vision science suggests that there is an image quality benefit over allocating the 16th bit to either red or blue.

3.0 Results

Figure 10 illustrates the difference between the processed and unprocessed image frame. When the processed (compensated) image frame sequences are displayed sequentially at the correct rate, the image appears correct (i.e. like that of the upper image) despite the slow response of the LCD due to the pre-correcting of the image by the RTC processor. This TCON has been applied to both TN and IPS to date with the result of improving all gray-to-gray responses to within 1 frame.

Figure 10. *Original (upper) and RTC processed (lower) identical frames. Note the preprocessing to the right edges of the left moving tree in the lower figure. Previously dark areas to be rendered light are compensated lighter (A). Previously light areas to be rendered dark are compensated darker (B). Areas that don't change between frames are not affected.*

The availability of off-the-shelf circuitry, which can compensate out the slow response of the LCD, especially wide viewing angle modes, allows application of standard LCD modes to television applications. This fast responding correction together with impulse framing methods provides enabling technology to extend AMLCDs to large-area, high-quality, TV applications.

4. Acknowledgements

I'd like to thank Futoshi Hayashida and Jonathan Kerwin for their innovative work in the design of the RTC function into the timing controller product and Anil Kumar for his helpful software tools.

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