P-61: Grayscales by Cross Pairing of Select and Data Voltages in Liquid Crystal Displays

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Abstract

Thousands of grayscales are displayed by cross pairing of a few select and data voltages in liquid crystal display. Simple drivers, low voltage operation, flicker free operation even at low refresh rates and good uniformity due to less distortion in addressing waveforms are the advantages of cross pairing.

1. Introduction

Quality of images is determined by the number of grayscales and conventional methods to display grayscales in LCD have some disadvantages. For example, data drivers of amplitude modulation (AM) [1] are complex because data waveforms have hundreds of voltages. Data drivers of AM have digital-to-analog converters (8 to10-bits) to drive columns of LCD. Pulse height modulation (PHM) [2] has more voltages in data waveforms but the number of time intervals is less as compared to AM because all address lines are selected simultaneously. Data drivers of successive approximation technique (SAT) [3] have simpler circuit because the number of voltages in data waveforms is small ($2 \cdot \log_2 G$ wherein G is the number of grayscales). However, the number of frames to display grayscales is high ($\log_2 G$) as compared to just two frames of AM. "Is it possible to achieve more grayscales than that of SAT with less number of frames?" Addressing this question has led to a phenomenal increase in number of grayscales with lesser number of frames (or time intervals) and fewer data voltages as compared to SAT. Cross pairing of select and data voltages in addressing waveforms can yield about 200, 2000 and 20,000 grayscales as compared to 16, 32 and 64 grayscales of successive approximation technique!

2. Principle

Amplitude of select voltage is chosen to be $\sqrt{N}$ times the amplitude of data voltages in addressing techniques of RMS responding LCD [4]-[7] to achieve the maximum selection ratio

(SR)= $\sqrt{(\sqrt{N}+1)/(\sqrt{N}-1)}$; wherein, N is the number of address lines (rows) multiplexed in LCD. This one-to-one correspondence between amplitudes of select and data voltages is maintained during all time intervals in SAT. Four unique RMS voltages are generated with two select pulses as in SAT and the corresponding data waveforms are shown in Figure 1(a). Same waveforms are used for complementary grayscales during polarity reversal of select pulses to ensure dc free operation. Amplitude of data voltages is proportional to that of select pulse in SAT when pixels are selected to scan the display. It is important to note that the maximum selection ratio is determined by RMS voltages of ON and OFF states. The intermediate RMS voltages of grayscales do not affect the selection ratio. Additional RMS voltages can be generated without affecting the maximum SR by cross pairing of select and data voltages with the technique proposed in this paper. It is not necessary to ensure that the amplitude of data voltages is

(a) Data waveforms similar to that of SAT

(b) Data wavforms that will form cross pairs

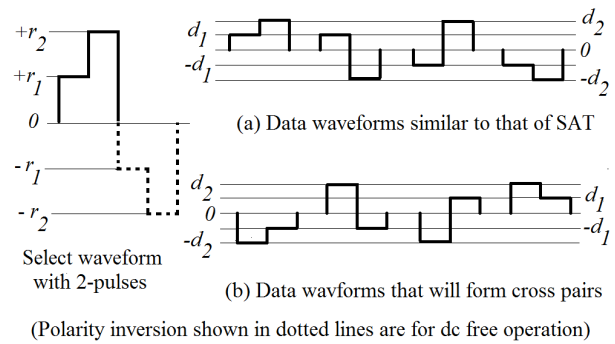(Polarity inversion shown in dotted lines are for dc free operation)

Figure 1. Select waveform with two select pulses is shown along with eight data waveforms. (a) Data waveforms at the top are similar to that of successive approximation technique. (b) Data waveforms that will lead to cross pairing of select and data voltages are shown below.

$\sqrt{N}$ times smaller than the amplitude of select voltage if the pixels are driven to intermediate grayscales. Cross pairing enables additional combinations of select and data voltages that are useful to generate RMS voltages with a value that are intermediate to RMS voltages of ON and OFF pixels. For example, let r_1 and r_2 be the amplitudes of select pulses. Let d_1 and d_2 be the amplitudes of data voltages. Addressing waveforms are made dc free by reversing the polarity of select and data voltages. Hence, the addressing waveforms will have four distinct select voltages ($+r_1$, $-r_1$, $+r_2$ and $-r_2$), a non-select voltage (0) and four data voltages ($+d_1$, $-d_1$, $+d_2$ and $-d_2$) as shown in Figure 1. In SAT r_1 will be paired either with $+d_1$ or $-d_1$ and not with $\pm d_2$. Similarly, r_2 would be paired with $+d_2$ or $-d_2$ and not with $\pm d_1$ during the select time. Hence, the four unique RMS voltages of SAT are shown here.

$$V_{++} \propto \sqrt{(r_1-d_1)^2 + (r_2-d_2)^2 + (N-1) \cdot (d_1^2+d_2^2)} \qquad (1)$$

$$V_{+-} \propto \sqrt{(r_1-d_1)^2 + (r_2+d_2)^2 + (N-1) \cdot (d_1^2+d_2^2)} \qquad (2)$$

$$V_{-+} \propto \sqrt{(r_1+d_1)^2 + (r_2-d_2)^2 + (N-1) \cdot (d_1^2+d_2^2)} \qquad (3)$$

$$V_{--} \propto \sqrt{(r_1+d_1)^2 + (r_2+d_2)^2 + (N-1) \cdot (d_1^2+d_2^2)} \qquad (4)$$

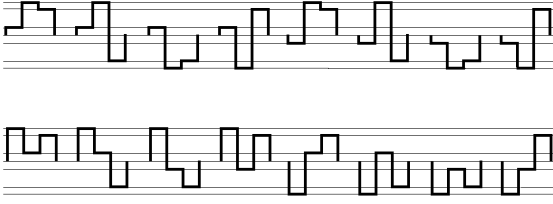Wherein $|r_i| = \sqrt{N} \cdot |d_i|$ \qquad (5)

Figure 2. Some of the 48 data waveforms that can be applied to columns when select waveform having three select pulses with their amplitudes in the ratio 2:7:9 are applied to a row. This ratio is not unique; a large number of grayscales can be generated with infinite sets of ratios of select pulses for cross pairing.
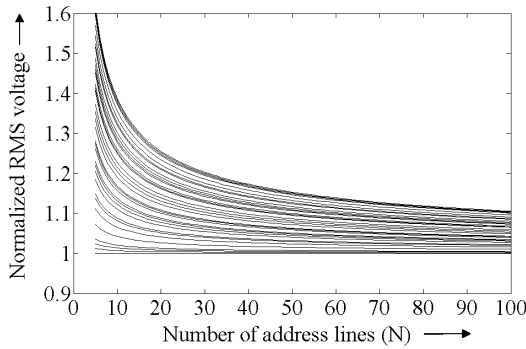

Figure 3. Plots of root-mean-square (RMS) voltages generated by cross pairing of select and data voltages as a function of N, number of address lines that are multiplexed. All RMS voltages are normalized to RMS voltage across OFF pixels in these plots.

The condition $r_{i+1} = \sqrt{2} \cdot r_i$ of SAT is relaxed in this technique. Three additional RMS voltages are generated by cross pairing of select and data voltages as shown in (6) to (8).

$$V_{\times++} \propto \sqrt{(r_1 - d_2)^2 + (r_2 - d_1)^2 + (N-1)\cdot(d_1^2 + d_2^2)} \quad (6)$$

$$V_{\times+-} \propto \sqrt{(r_1 + d_2)^2 + (r_2 - d_1)^2 + (N-1)\cdot(d_1^2 + d_2^2)} \quad (7)$$

$$V_{\times--} \propto \sqrt{(r_1 + d_2)^2 + (r_2 + d_1)^2 + (N-1)\cdot(d_1^2 + d_2^2)} \quad (8)$$

The number of unique RMS voltages obtained by cross pairing increases rapidly with the number of select pulses. Number of additional voltages obtained by cross pairing is 26, 209 and 1914 respectively in cases of 3, 4 and 5 select pulses.

3. Technique

The cross pairing method is illustrated with three select pulses. Let $\pm\alpha$, $\pm\beta$, and $\pm\delta$ be the six data voltages. Amplitude of select voltages are chosen to be $\sqrt{N}\alpha$, $\sqrt{N}\beta$, and $\sqrt{N}\delta$ respectively to achieve the maximum selection ratio. The first select voltage; for

example: $\sqrt{N}\alpha$ can be paired with any one of the six data voltages to be applied simultaneously to a row and a column of LCD for a period T. The choice of data voltage gets restricted to 4 and 2 respectively for the second and third select pulses because data voltage of certain amplitude is used just once to ensure that the voltages across non-selected pixels are independent of the state of the selected pixels to avoid crosstalk. Expressions of RMS voltage across pixels consist of two major terms as shown in (9).

$$V_{RMS} \propto \sqrt{\frac{\sum_{Select} Vi^2 + \sum_{Non-select} Vi^2}{\text{number of select pulses} \times N}} \quad (9)$$

The first term in the numerator corresponds to summation of square of instantaneous voltage (Vi) across a pixel during select time intervals when pixels are selected by applying select pulses to one of the address lines. The second term in (9) is the summation of square of instantaneous voltages across the same pixel when pixels in all other (N-1) address lines are selected. The second term shown in (10) is independent of the state of pixels and only the first terms that control the state of pixels are shown in (11) to (18) for the sake of clarity and to conserve space.

$$(N-1))\cdot(\alpha^2 + \beta^2 + \delta^2) \quad (10)$$

$$(\sqrt{N}\alpha - \alpha)^2 + (\sqrt{N}\beta - \beta)^2 + (\sqrt{N}\delta - \delta)^2 \quad (11)$$

$$(\sqrt{N}\alpha - \alpha)^2 + (\sqrt{N}\beta - \beta)^2 + (\sqrt{N}\delta + \delta)^2 \quad (12)$$

$$(\sqrt{N}\alpha - \alpha)^2 + (\sqrt{N}\beta + \beta)^2 + (\sqrt{N}\delta - \delta)^2 \quad (13)$$

$$(\sqrt{N}\alpha - \alpha)^2 + (\sqrt{N}\beta + \beta)^2 + (\sqrt{N}\delta + \delta)^2 \quad (14)$$

$$(\sqrt{N}\alpha + \alpha)^2 + (\sqrt{N}\beta - \beta)^2 + (\sqrt{N}\delta - \delta)^2 \quad (15)$$

$$(\sqrt{N}\alpha + \alpha)^2 + (\sqrt{N}\beta - \beta)^2 + (\sqrt{N}\delta + \delta)^2 \quad (16)$$

$$(\sqrt{N}\alpha + \alpha)^2 + (\sqrt{N}\beta + \beta)^2 + (\sqrt{N}\delta - \delta)^2 \quad (17)$$

$$(\sqrt{N}\alpha + \alpha)^2 + (\sqrt{N}\beta + \beta)^2 + (\sqrt{N}\delta + \delta)^2 \quad (18)$$

The eight expressions (11)-(18) can be compactly represented by an expression in (19) to conserve space.

$$(\sqrt{N}\alpha \pm \alpha)^2 + (\sqrt{N}\beta \pm \beta)^2 + (\sqrt{N}\delta \pm \delta)^2 \quad (19)$$

Additional compact expressions that are obtained by cross pairing of select and data voltages are as follows.

$$(\sqrt{N}\alpha \pm \beta)^2 + (\sqrt{N}\beta \pm \delta)^2 + (\sqrt{N}\delta \pm \alpha)^2 \quad (20)$$

$$(\sqrt{N}\alpha \pm \alpha)^2 + (\sqrt{N}\beta \pm \delta)^2 + (\sqrt{N}\delta \pm \beta)^2 \quad (21)$$

$$(\sqrt{N}\alpha \pm \delta)^2 + (\sqrt{N}\beta \pm \beta)^2 + (\sqrt{N}\delta \pm \alpha)^2 \quad (22)$$

$$(\sqrt{N}\alpha \pm \beta)^2 + (\sqrt{N}\beta \pm \alpha)^2 + (\sqrt{N}\delta \pm \delta)^2 \quad (23)$$
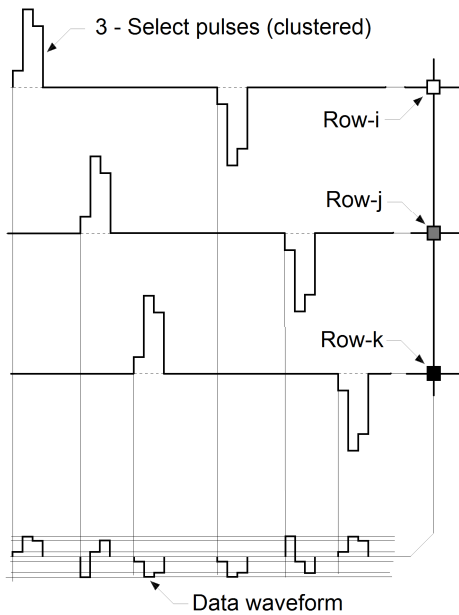
Figure 4. Typical addressing waveforms when 3 select pulses are used to scan the rows. Thirty four grayscales can be displayed with six voltages in data waveforms and seven voltages in select waveforms. The select pulses and the corresponding data pulses may also be distributed into different frames instead of clustering them as shown in this figure to reduce flicker and suppress frame response phenomenon in fast responding LCD.

Cross pairing shown in (19), (20), (21) and (22) contribute to 8, 6, 6 and 6 unique expressions of RMS voltages for grayscale. Amplitude of each data voltage appears just once; either in phase or out of phase with the select pulse but not both in the expression of (19) - (22) so that the instantaneous voltages during non-select duration contribute to the constant term of (10).

Expressions for each of the 34 unique RMS voltages can be obtained substituting the terms from (19)-(22) and (10) into the expression in (9). For example RMS voltage of one of the six combinations of (23) is as follows:

$$\sqrt{\frac{(\sqrt{N}\alpha+\beta)^2+(\sqrt{N}\beta-\alpha)^2+(\sqrt{N}\delta+\delta)^2+(N-1)(\alpha^2+\beta^2+\delta^2)}{3N}}$$

$$(24)$$

$$V_{RMS}=\sqrt{\frac{2N(\alpha^2+\beta^2+\delta^2)+2\sqrt{N}\delta^2}{3N}}$$

$$(25)$$

Expressions of RMS voltages are used to determine the data voltages for each grayscale and the data voltages are permanently stored into a lookup table. The display is scanned by selecting one row at a time and each row is selected with one or multiple select pulses. Data voltages are applied to all columns of the display based on the desired grayscale of pixel in selected row by using the lookup table along with the select pulse. A cycle is complete when all rows in the matrix display are selected with each of the three select pulses once. Plots of RMS voltages as functions the number of address lines are shown in Figure 3. Typical waveforms of the technique are shown in Figure 4 when 3 select pulses are used to scan the display. The number of voltages in
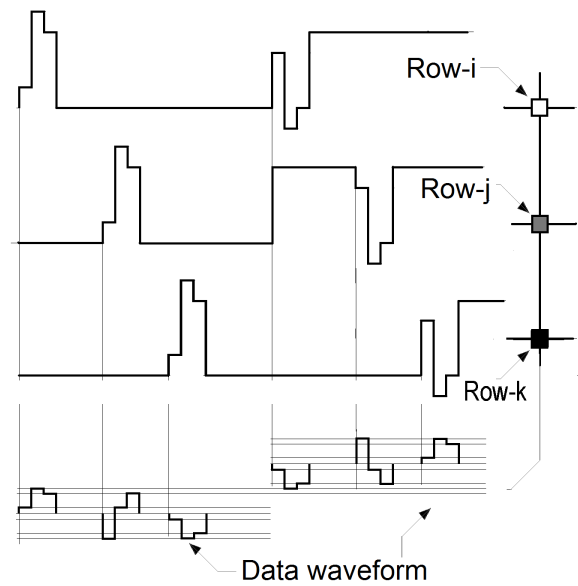

Figure 5. Typical addressing waveforms when supply voltage of row drivers is reduced to about 50% (as compared to supply voltage of waveforms of Figure 4) by shifting the voltages in the addressing waveforms when select pulses are negative.

scanning waveforms is 7 that consist of 3 select pulses, 3 additional select pulses of negative polarity to achieve dc free waveforms across pixels and a non-select voltage. Data waveforms have six voltages. Both row and column drivers are simple and 34 grayscales can be displayed with 3 frames. The ratio of select pulses is 2:7:9; it is not an unique combination. For example 1:4:5 can also yield 34 unique RMS voltages. Supply voltage of the drive circuit is proportional to $2\sqrt{N}$ and it can be reduced to be proportional to $\left(\sqrt{N}+1\right)$ by shifting both the select as well as data voltages when select voltages are negative as shown in Figure 5. It is similar to the method proposed by Kawakami et al [6] to reduce the supply voltage of the drivers for the conventional line-by-line addressing technique. In summary it is a line by line addressing technique with multiple select pulses wherein the ratio of amplitude of select voltage to that of data voltage is maintained to be $\sqrt{N}$ only when pixels are driven either to ON or OFF state and such condition is not adhered to when pixels are driven to intermediate grayscale. The number of unique RMS voltages is 225 and 1946 respectively for four and five select pulses respectively as compared to 16 and 32 of SAT. Number of unique RMS voltages is about 20000 when six select pulses are employed in the addressing technique! Space available is inadequate to list all expressions of RMS voltages when the number of select pulse is greater than 3. However, the principle explained in section 2 along with the illustration for 3 select pulses provide adequate information to extend the technique for higher number of select pulses. It is also possible to generate uniformly spaced RMS voltages although it is not necessary here because electro-optic response of LCD is not linear and RMS voltages are not equally spaced when gamma correction is applied. For example; 85 uniformly spaced RMS voltages can be
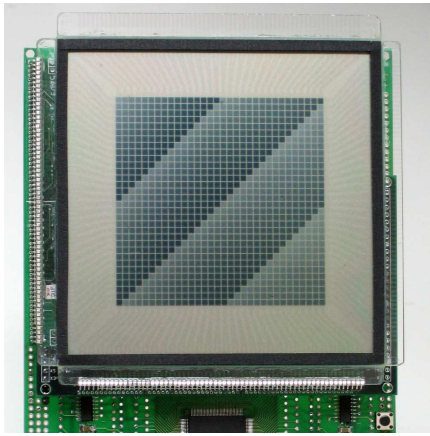
Figure 6. Photograph of the prototype display that demonstrates grayscale technique based on cross pairing of select and data voltages.
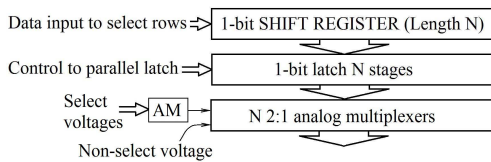

Figure 7. Row driver to display grayscales based on cross pairing of select and data voltages. Note: N is the number of rows in the matrix display.
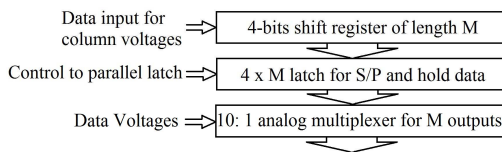

Figure 8. Data driver to display 1946 grayscales with cross pairing technique that is ideal for 10-bit grayscales with gamma correction. Note: M-is the number of columns in the matrix display and AM is the 2:1 analog multiplexer.

generated with four select pulses with their amplitudes in the ratio 1:3:5:7. However the number of RMS voltages is far less than the 225 unique RMS voltages that can be achieved with four select pulses without any constraint on the difference between neighboring RMS voltages which are any way very close to each other.

3.1. Gamma (γ)-Correction
Gamma correction can be incorporated easily because the number of unique voltages is large and they form a band of voltages as evident from Figure 3. Lookup table of data voltages can directly incorporate the gamma correction which depends on the electro-optic response of the LCD

4. Results
Photograph of a prototype that is designed to display 64 grayscales with four select pulses in the addressing waveforms is shown in Figure 6. The ratio amplitude of select pulses is 1:3:5:7. Block diagram of row drivers for this technique is shown in Figure 7 and block diagram of data driver to display 1946 grayscales is shown in Figure 8.

5. Impact
Number of data voltages is just 10 to display 1024 grayscales with the proposed cross pairing as compared to 2048 voltages in case of AM [1]. Number of data voltages is also reduced to 50% with the proposed cross pairing method as compared to successive approximation technique (10 voltages as compared to 20 data voltages in case of SAT to display 1024 grayscales). Supply voltage of drivers is less by 12% as compared to the successive approximation technique. Row select time of the proposed technique is twice that of successive approximation technique when 1024 grayscales are displayed (100% increase). Therefore, distortion in the addressing waveforms due to RC time constant will be less as compared to successive approximation technique due to wider select pulses leading to a better brightness uniformity of pixels that are driven to same state.

6. Acknowledgements
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7. References
[1] T. N. Ruckmongathan, "Addressing techniques for RMS responding LCDs - A review", Proc. Japan Display '92, 77-80, (1992).

[2] A. R. Conner and T. J. Scheffer, "Pulse-height modulation (PHM) gray shading methods for passive matrix LCDs," Proc. of Japan Display'92, 69-72, (1992).

[3] T. N. Ruckmongathan, A Successive Approximation Technique for Displaying Gray Shades in Liquid Crystal Displays (LCDs)", IEEE transactions on Image Processing, Vol.16, No.2, 554-561, (2007).

[4] J. E. Bigelow, R. A. Kashnow, and C. R. Stein, "Contrast optimization in matrix-addressed liquid crystal displays", IEEE Trans. Electron Devices, vol. ED-22, 22, (1975).

[5] J. Nehring and A.R. Kmetz, "Ultimate Limits for Matrix Addressing of RMS Responding Liquid Crystal Displays", *IEEE Transactions on Electron Devices*, Vol. ED-26, 795 – 802, (1979)

[6] P.M. Alt and P. Pleshko, "Scanning Limitations of Liquid Crystal Displays", *IEEE Transactions on Electron Devices*, Vol. ED-21, 146 – 155, (1974)

[7] Kawakami et al, "Matrix addressing technology of twisted nematic displays", SID-IEEE conference record of Biennial Display Research Conference, 50-52 (1976).