11.3: Wavelets for Displaying Gray Shades in LCDs

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Abstract
A technique that relies on integer wavelets to deliver energy to pixels and display gray shades in rms responding matrix displays is proposed. A large number of gray shades can be displayed without flicker using simple addressing waveforms with a few voltage levels.

1. Introduction
Quality of images in a display depends on its resolution, contrast and the number of colors. Number of gray shades in the three primary colors of a pixel decides the number of colors that can be displayed. Our objective is to display gray shades in liquid crystal displays (LCDs) with simple addressing waveforms. It is preferable that the technique for displaying gray shades does not increase the cost of the drive electronics. Techniques for displaying gray shades in passive matrix LCDs are reviewed briefly in the following section.

2. Background
Most of the techniques for displaying gray shades in passive matrix LCDs have some drawback. The number of time intervals to display (k+1) gray shades is (k) if frame rate control [2] or pulse width modulation [3] is used. About eight to sixteen gray shades can be displayed using frame modulation without flicker. The number of time intervals (k) is logarithm of the number of gray shades (2^k) in row pulse modulation [4] and successive approximation [5] techniques. Hence, these techniques are better as compared to frame modulation when the number of gray shades to be displayed is large. However, selection ratio of row pulse modulation is low as compared to the maximum selection ratio in equation (1).

$$\text{Selection Ratio}_{\text{maximum}} = \sqrt{\frac{\sqrt{N}+1}{\sqrt{N}-1}} \qquad (1)$$

Successive approximation technique achieves the maximum selection ratio. Para-unitary matrices have also been used to display gray shades [6]. Amplitude modulation [7] (also referred to as pulse height modulation) can be used to display a large number of gray shades with two time intervals. However, it demands the use of analog type column drivers because the number of voltages in the column waveforms is large. These drivers consume more power as compared to the digital drivers that select one of the several voltages using analog multiplexers. We have explored the possibility of using integer wavelets for displaying gray shades in root mean square (RMS) responding LCDs. We have modified wavelets to display eight gray shades in a *32x32* matrix LCD as described in the next section.

3. Technique
The technique is based on using wavelets to deliver energies that are proportional to the binary weight of the bits in the gray shade data of pixels. We have selected the Haar wavelets [1] and modified them so that the amplitudes of these wavelets are integers and the energies of these wavelets are in powers of two. We have chosen the Haar wavelets because they are simple and orthogonal. The corresponding waveforms have a few voltage levels and hence, they are easy to generate. A 4x4 Haar matrix is shown in the following equation.

$$\begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & +1 & -1 & -1 \\ +\sqrt{2} & -\sqrt{2} & 0 & 0 \\ 0 & 0 & +\sqrt{2} & -\sqrt{2} \end{bmatrix} \qquad (2)$$

Amplitudes of the Haar functions are such that the energies of these wavelets are equal. However, we have modified the amplitudes of these wavelets such that the energy of each wavelet corresponds to a binary weight of the gray shade data. Hence, the energy of each wavelet is unique and these energies are in powers of two. In the matrix shown in equation (3), each wavelet is associated with one bit of the gray shade data. For example, the wavelet in the first row has the highest energy among the three rows and it is associated with the most significant bit (MSB) of the gray shade. Wavelet in the second row corresponds to the middle bit because its energy is lower than that of the first row. Wavelet in the last row has the least energy and it is associated with the least significant bit (LSB) of the gray shade.

$$Wg_{3x4}(8,4,2) = \begin{bmatrix} 0 & 0 & +2 & -2 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & 0 & 0 \end{bmatrix} \qquad (3)$$

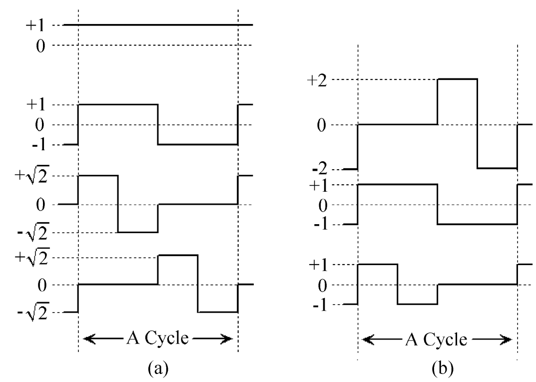

Figure 1 (a) Haar wavelets and (b) the modified wavelets

The Haar wavelets are shown in Figure 1(a) and the modified wavelets corresponding to the matrix of equation (3) are shown in Figure 1(b). The rows in the matrix display are grouped to form subgroups, each consisting of three rows. If N is not an exact multiple of three, then one or two dummy rows may be added so that (N/3) is an integer. At a given instant of time, a subgroup is selected with voltages corresponding to a select pattern i.e. one of the columns in the matrix of wavelets in equation (3). Most significant bit is used as the data for all the pixels in the first row of the selected subgroup because it is selected with a wavelet having the highest energy. The next significant bit of the gray

 ISSN/0005-0966X/05/3601-0168-$1.00+.00

shade is used as the data for the pixels in the middle row of the selected subgroup. The least significant bit of the gray shade data is used as the data for the last row. These three bits of the pixels in the selected rows and a column constitute the data vector of that column. Column signal is the dot product of the select pattern with the data vector. The column signals for other columns in the matrix display are computed in the same manner by using the data of the pixels in the selected rows. Voltages corresponding to the select pattern and column signals are applied simultaneously to the rows and columns of the matrix display for a time duration referred to as the select time. The unselected rows are connected to the mid voltage (zero). A scan is complete when all the subgroups in the matrix display have been selected with the four select patterns in the matrix of equation (3). At this stage, the energy delivered to the pixels in the first, second and third row of the subgroups is proportional to 8,4 and 2 respectively. The next scan of the display is performed using the matrix in equation (4), so that the energies delivered to the pixels in the first, second and third rows of the selected subgroup are proportional to 4, 2, and, 8 respectively.

$$Wg_{3x4}(4,2,8) = \begin{bmatrix} 1 & 1 & -1 & -1 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 2 & -2 \end{bmatrix} \qquad (4)$$

Column signals for this scan are computed using the data vector formed with the middle, least, and most significant bits of the pixels in the first, second and third rows respectively of the selected subgroup. Similarly, the last scan uses the least, most and middle significant bits of pixels in the first, second and third rows of the selected subgroup as the data vector. The orthogonal matrix for the third scan is shown in equation (5).

$$Wg_{3x4}(2,8,4) = \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 2 & -2 \\ 1 & 1 & -1 & -1 \end{bmatrix} \qquad (5)$$

The three scans deliver energies corresponding to the three bits of the gray shade data. This cycle is repeated to refresh the display continuously. The twelve select patterns of a refresh cycle are shown in the matrix of equation (6).

$$\begin{bmatrix} 0 & 0 & +2 & -2 & +1 & +1 & -1 & -1 & +1 & -1 & 0 & 0 \\ +1 & +1 & -1 & -1 & +1 & -1 & 0 & 0 & 0 & 0 & +2 & -2 \\ +1 & -1 & 0 & 0 & 0 & 0 & +2 & -2 & +1 & +1 & -1 & -1 \end{bmatrix} \qquad (6)$$

The data bits of a column for each select pattern (columns of the matrix in equation (6)) are shown in the corresponding columns of the matrix in the following equation.

$$\begin{bmatrix} x & x & d_3 & d_3 & d_2 & d_2 & d_2 & d_2 & d_1 & d_1 & x & x \\ d_2 & d_2 & d_2 & d_2 & d_1 & d_1 & x & x & x & x & d_3 & d_3 \\ d_1 & d_1 & x & x & x & x & d_3 & d_3 & d_2 & d_2 & d_2 & d_2 \end{bmatrix} \qquad (7)$$

Here, each element of the matrix represents a bit of the gray shade data i.e. d_3 is the most significant bit, d_2 is the middle bit, d_1 is the least significant bit and x represents 'don't cares' because the corresponding element of the select pattern is zero. For example, the most significant bit of the pixels in the first row, middle bit of the pixels in the second row and least significant bit of the pixels in the last row of a subgroup are the elements of the data vector, when the select patterns shown in equation (8) are used to select the rows. Just two of the three elements of the data vector are used for computation of the dot products as evident from equation (7)

$$\begin{bmatrix} 0 \\ +1 \\ +1 \end{bmatrix} \text{or} \begin{bmatrix} 0 \\ +1 \\ -1 \end{bmatrix} \text{or} \begin{bmatrix} +2 \\ -1 \\ 0 \end{bmatrix} \text{or} \begin{bmatrix} -2 \\ -1 \\ 0 \end{bmatrix} \qquad (8)$$

Column voltage for a specific select pattern is obtained by the dot product of that select pattern with the data vector in the corresponding column of the matrix in the equation (6). The order in which the select patterns are used to select the rows may be changed as long as the corresponding data vector is used for computing the column signal. For example, columns of the matrix in equation (6) are rearranged in the following orders (1, 7, 3, 2, 8, 4, 11, 9, 5, 12, 10, and 6) to ensure that zeros do not cluster together. The rearranged matrix is shown in equation (9).

$$\begin{bmatrix} 0 & -1 & +2 & 0 & -1 & -2 & 0 & +1 & +1 & 0 & -1 & +1 \\ +1 & 0 & -1 & +1 & 0 & -1 & +2 & 0 & +1 & -2 & 0 & -1 \\ +1 & +2 & 0 & -1 & -2 & 0 & -1 & +1 & 0 & -1 & +1 & 0 \end{bmatrix} \qquad (9)$$

The corresponding matrix of data vector is as follows.

$$\begin{bmatrix} x & d_2 & d_3 & x & d_2 & d_3 & x & d_1 & d_2 & x & d_1 & d_2 \\ d_2 & x & d_2 & d_2 & x & d_2 & d_3 & x & d_1 & d_3 & x & d_1 \\ d_1 & d_3 & x & d_1 & d_3 & x & d_2 & d_2 & x & d_2 & d_2 & x \end{bmatrix} \qquad (10)$$

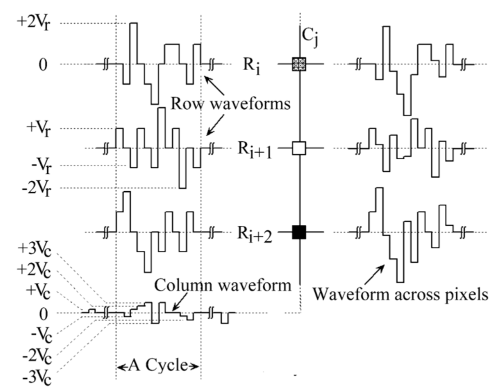

Figure 2 Typical addressing waveforms

In summary, the column signal is the dot product of the select pattern and the corresponding data vector. A voltage proportional to the column signal is applied to that column while the rows are selected with voltages that are proportional to the elements of the select pattern. A cycle is complete when all the subgroups of rows are selected with all the select patterns i.e. all the columns of matrix in equation (6) or equation (9) or any other matrix formed by interchanging the columns of matrix in equation (6). Typical waveforms, when the rows of a subgroup are selected with all the select patterns before selecting the next subgroup are shown in Figure 2. As evident from the figure, the waveforms across the pixels are dc free because the rows are selected with dc free wavelets. The technique can be extended to display large number of gray shades. For example, the matrix shown in the equation (11) can be used to display 32 gray shades with just five and nine voltages in the row and column waveforms respectively. This matrix may not be the optimum one to minimize the number of voltages in the addressing waveforms, but it illustrates the potential of wavelets to displaying a large number of gray shades.

$$\begin{bmatrix} +2 & +2 & +2 & +2 & -2 & -2 & -2 & -2 \\ +2 & +2 & -2 & -2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & -2 & 0 & 0 \\ 0 & 0 & 0 & 0 & +1 & +1 & -1 & -1 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (11)$$

The hardware implementation of this technique to display eight gray shades is described in the next section.

4. Implementation

The technique has been demonstrated using a 32x32 matrix display. The thirty-two rows of the LCD are divided into eleven subgroups, each having three rows (after adding a dummy row). A block diagram of the prototype is shown in Figure 3.

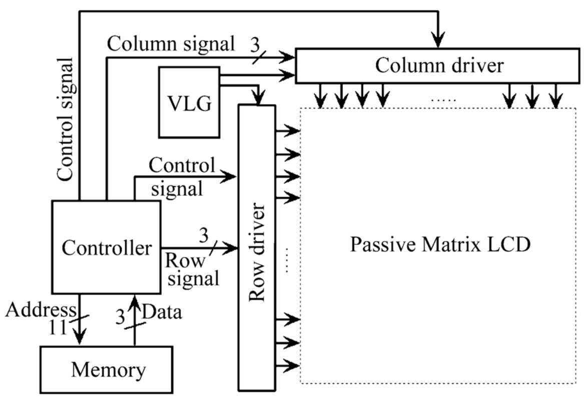

Figure 3 A Block diagram of the prototype

4.1 Voltage Levels

The row waveforms have five voltage levels $\left(-2V_r, -V_r, 0, +V_r, \text{and} +2V_r\right)$ corresponding to the elements of the orthogonal matrix. The column waveforms have seven voltages $\left(-3V_c, -2V_c, -V_c, 0, +V_c, +2V_c, \text{and} +3V_c\right)$ that are proportional to the column signals. These voltages are generated in the Voltage Level Generator (VLG) and are fed to the respective drivers. A resistor network is used to generate these voltages.

4.2 Drivers

The row and column drivers use SED 1180 (LCD segment driver) and CD 4051 (8:1 analog multiplexers). The SED1180 has 64 outputs to drive the columns of line-by-line addressed LCDs. Although it cannot be used directly, we have used the forty-eight stages (out of the sixty-four stages) of shift register and latch in this driver. Two SED 1180 have been used in the printed circuit board of each driver. Outputs of these stages are connected to the select signals of thirty-two analog multiplexers. Each multiplexer (one for each output of the driver) selects one of the eight voltages from the voltage level generator depending on the select signal.

4.3 Controller

A controller has been designed to carry out the following scanning sequence. The first subgroup is selected with a (first) select pattern and the second subgroup is selected with another (second) select pattern. This process is continued until all (eleven) of the subgroups are selected once with a select pattern. Then the first subgroup is selected with a new (second) select pattern and the process is continued until all the rows have been selected with the twelve (all) select patterns once. This scanning sequence is used to suppress the frame response in fast responding LCDs, improve brightness uniformity of pixels and reduce flicker. Typical waveforms of this scanning sequence are shown in Figure 4.

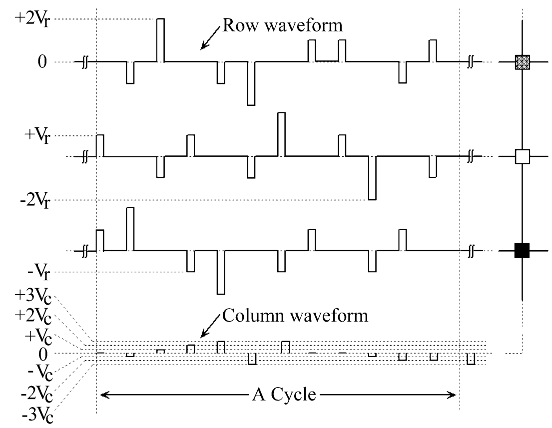

Figure 4 Typical waveforms with distributed select pulses

4.3.1 *Row signal*

A Look up table (LUT) is used to store the twelve select patterns. Elements of the select pattern are shifted into the three stages of the shift register (in the row driver) that correspond to the selected rows. Zeros are shifted into all other stages of the shift register since they correspond to non-selected rows. Valid row signals are (010), (001), (000), (111) and (110) and they correspond to the elements of the select pattern i.e., 2,1,0, -1 and –2 respectively.

4.3.2 *Column signal*

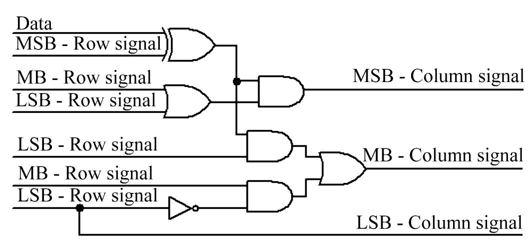

Figure 5 A multiplier for generating the column signal

The column signal is the dot product of the select pattern and the data vector. The elements of the data vector depend on the select pattern as discussed earlier. Elements of the select pattern are represented in 2's complement notation. A +1 or –1is assigned to the elements of the data vector corresponding to logic '0' or logic '1' respectively. A multiplier has been designed to obtain the partial product of an element of select pattern with a data bit. Column signal is generated by adding three such partial products. Output of the adder is an integer in the range –3 to +3. The schematic of the multiplier is shown in Figure 5.

4.3.3 Control signals

The controller reads the data from the memory and generates the row and column signals that are loaded into the respective drivers. Control signals like clock for the shift register, latch pulse, enable signals for the clock, chip enable etc. are also generated by the controller. All the control signals are derived from a clock so that the refresh rate can be varied by changing the clock frequency. The display refresh rate is 50 Hz when the clock frequency is about 630 kHz. Simple patterns like horizontal, vertical and diagonal bars of gray shades as well as mirror image of these patterns are generated in the controller. The controller is used to display either an image from the memory or the simple patterns generated inside the controller (for diagnostics of the display system). The controller has been implemented on a Complex Programmable Logic Device (CPLD) using about hundred logic cells.

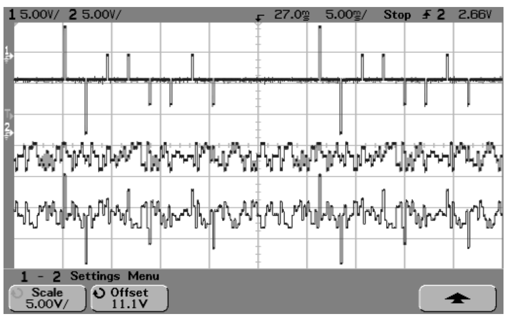

Figure 6 Photograph of typical waveforms

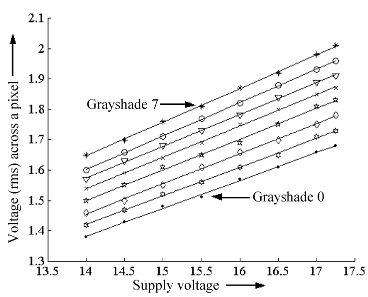

Figure 7 Plot of RMS voltage vs. supply voltage

5. Results

Typical waveforms i.e. row waveform (top), column waveform (middle) and the waveform across a pixel (bottom) are shown in Figure 6. The waveforms across the pixels are dc free. The RMS voltage across a pixel when displaying the eight gray shades vs. supply voltage has been plotted in Figure 7. Photograph of the prototype while displaying a simple geometric pattern and an image are shown in Figure 8.

6. Conclusion

The technique that has been proposed needs just k time intervals to display 2^k gray shades. It achieves the maximum selection ratio given in equation (1). Although, this technique is based on multi-line addressing [8], the number of voltage levels is small considering the fact that multi-line addressing techniques have at least (k+1) voltages in the column waveforms even while displaying binary images. Hardware complexity of the column drivers has been reduced with a marginal increase in the complexity of row drivers. The technique opens up the possibility of displaying a large number of gray shades using relatively simple column drivers. Although we have demonstrated the technique for eight gray shades, a large number of gray shades can be displayed by using Haar or any other orthogonal wavelets. This would further enhance the use of LCDs in portable devices viz., mobile phones, personal digital assistant etc.

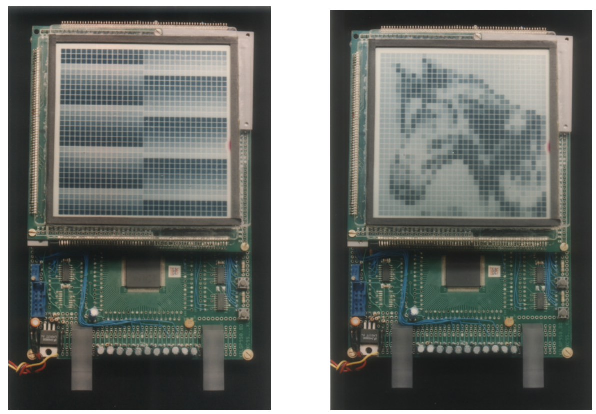

Figure 8 Photographs of the prototype

Acknowledgements

We express our thanks to Shashidhara for fabricating the LCD and Mani for his help in fabricating the prototype.

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