Integer Wavelets for Displaying Gray Shades in RMS Responding Displays

T. N. Ruckmongathan, U. Manasa, R. Nethravathi, and A. R. Shashidhara

***Abstract*—A large number of gray shades can be displayed in rms responding displays by using integer wavelets. The technique is demonstrated by displaying 64 gray shades in a twisted nematic liquid crystal display. We have reduced the hardware complexity of the display drivers by adding a few analog multiplexers that are common to a large number of stages (one for each output) in the drivers. A simple controller was implemented in a low cost complex programmable logic device.**

***Index Terms*—Gray shades, liquid crystal displays (LCDs), matrix addressing, multi-line addressing (MLA), wavelets.**

I. Introduction

THE CAPABILITY to display a large number of gray shades is desirable to increase the number of colors and to avoid gray scale contours in images. A larger number of gray shades can be displayed using amplitude modulation [1], successive approximation [2] and wavelet [3] techniques. Several addressing techniques for displaying gray shades in rms responding matrix LCDs are reviewed in [4]. A technique [3] to display eight gray shades using wavelets was presented at the Society for Information Display conference as a proof of the concept. A technique with good reduction in hardware complexity of the drive electronics (drivers as well as the controller) when a large number of gray shades are displayed using integer wavelets is presented in this paper.

II. Technique

The technique is illustrated with the Haar wavelets, as they are simple and easy to generate. A similar procedure can be followed for scanning the matrix with other wavelets. The first step is to construct an orthogonal matrix because multiplexing the data to the pixels in the display is possible when the matrix display is scanned with waveforms derived from orthogonal functions or matrices. Selection of wavelets and the construction of an orthogonal matrix with them are described in the next section.

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A. Construction of an Orthogonal Matrix Based on Wavelets

A set of Haar wavelets is chosen and the amplitude of the wavelets are modified such that the following conditions are satisfied:

1) amplitude of the wavelets is an integer;
2) energy of a wavelet is equal to an integer power of two;
3) energy of each wavelet is chosen to correspond uniquely to weight of a bit in the gray shade data;
4) wavelets are DC free so that the waveforms across the pixels will also be DC free to ensure long life of the display.

A set of six wavelets satisfying these conditions are shown in (1)–(6).

$$w_{B5} = \{+4, +4, +4, +4, -4, -4, -4, -4\} \quad (1)$$
$$w_{B4} = \{+4, +4, -4, -4\} \quad (2)$$
$$w_{B3} = \{+4, -4\} \quad (3)$$
$$w_{B2} = \{+2, +2, -2, -2\} \quad (4)$$
$$w_{B1} = \{+2, -2\} \quad (5)$$
$$w_{B0} = \{+1, +1, -1, -1\}. \quad (6)$$

Energies of these wavelets are 128, 64, 32, 16, 8, and 4, respectively, and they are proportional ($\times 4$) to the weight of the most significant to the least significant bit of the gray shade data. Subscripts $B5$ to $B0$ in (1)–(6) correspond to the binary digit (bit) of the gray shade data. The gray shade value $g_{i,j}$ ranges from -63 to $+63$ in steps of 2 as shown in the following expression:

$$g_{i,j} = \sum_{k=0}^{5} 2^k . d_k; \quad d_k = \begin{cases} +1 & \forall \quad \text{logic } 0 \\ -1 & \forall \quad \text{logic } 1 \end{cases}. \quad (7)$$

The wavelets in (1)–(6) are combined to form an orthogonal matrix, as shown in (8)

$$O(1)_{4\times 8} = \begin{bmatrix} +4 & -4 & +4 & -4 & +4 & -4 & +4 & -4 \\ +2 & 0 & -2 & 0 & +2 & 0 & -2 & 0 \\ 0 & +4 & 0 & -4 & 0 & +4 & 0 & -4 \\ +2 & +1 & +4 & -1 & -2 & -1 & -4 & +1 \end{bmatrix}. \quad (8)$$

Although it is possible to obtain an orthogonal matrix with just three rows, the number of rows is chosen to be four to reduce the hardware complexity of the controller. Columns of the orthogonal matrix in (8) are referred to as the select vectors. Each element of the orthogonal matrix corresponds to a bit of the gray shade data (d_i) as shown in the matrix $D(1)_{4\times 8}$ in (9)

$$D(1)_{4\times 8} = \begin{bmatrix} d_5 & d_5 & d_5 & d_5 & d_5 & d_5 & d_5 & d_5 \\ d_2 & 0 & d_2 & 0 & d_2 & 0 & d_2 & 0 \\ 0 & d_4 & 0 & d_4 & 0 & d_4 & 0 & d_4 \\ d_1 & d_0 & d_3 & d_0 & d_1 & d_0 & d_3 & d_0 \end{bmatrix}. \quad (9)$$

Several orthogonal matrices can be constructed with the wavelets in (1)–(6). Hence, the matrix in (8) is not a unique, for example the matrix in (10) and the associated data matrix in (11) could also be used for scanning the matrix LCDs.

$$O(1)_{4\times8}=\begin{bmatrix}+4&-4&+4&-4&+4&-4&+4&-4\\0&+2&0&-2&0&+2&0&-2\\+4&0&-4&0&+4&0&-4&0\\+4&+1&-2&-1&-4&-1&+2&+1\end{bmatrix} \quad (10)$$

$$D(1)_{4\times8}=\begin{bmatrix}d_5&d_5&d_5&d_5&d_5&d_5&d_5&d_5\\0&d_2&0&d_2&0&d_2&0&d_2\\d_4&0&d_4&0&d_4&0&d_4&0\\d_3&d_0&d_1&d_0&d_3&d_0&d_1&d_0\end{bmatrix}. \quad (11)$$

B. *Scanning the Matrix Display*

Consider a matrix display with N and M orthogonal electrodes with picture-elements (pixels) located at the intersection of these address lines. Let the gray shade of the pixel located at the intersection of row i and column j be $g_{i,j}$ as given in (7). The matrix display may be scanned either by selecting the row electrodes or the column electrodes. The electrodes that are used for scanning the display are called the scanning electrodes and the electrodes that are orthogonal to the scanning electrodes are referred to as the data electrodes. Let the number of scanning electrodes be N. These electrodes are grouped to form about $(N/4)$ sets of scanning electrodes each consisting of four electrodes. The display is scanned by selecting one set (four) of scanning electrodes at a time by applying voltages that are proportional to elements of the select vector. For example, the address lines can be selected by applying $-4V_r$, 0, $+4V_r$, and $+V_r$ when the second column of the matrix in (8) is the select vector, as shown in (12).

$$\begin{bmatrix}-4\\0\\+4\\+1\end{bmatrix}. \quad (12)$$

All the other $(N-4)$ non-selected scanning electrodes are grounded. Voltages for the data electrodes are obtained by computing the dot product of the select vector with the data vectors. The data vector is obtained by picking the bits of the gray shade data as dictated by the elements of the column in (9) that corresponds to the select vector. In our example, the bit-5 (MSB) of the pixels located on the first selected electrode, bit-4 of the pixels on the third selected electrode and bit-0 (LSB) of the pixels in the fourth selected electrode are used to form the data vector because the elements of the select vectors correspond to the wavelets in (1), (2), and (6) respectively. Second element of the data vector is zero because the corresponding element of the select vector is also zero. Data voltages for all the data electrodes in the display are computed by using the dot product as shown in (13).

$$V_{\text{data-}j}=\begin{bmatrix}-4\\0\\+4\\+1\end{bmatrix}\cdot\begin{bmatrix}d_5\\0\\d_4\\d_0\end{bmatrix}.V_c. \quad (13)$$

Select and data voltages are applied to the respective electrodes simultaneously during a time interval T, referred to as the select time. A frame is complete when all the $(N/4)$sets of scanning electrodes are selected with all the select vectors of (8). At the end of the frame, energy delivered to the pixels in the first electrode of all the sets is proportional to the most significant bit of the gray shade data because the energy of the wavelet in the first row of the orthogonal matrix in (8) corresponds to the most significant bit. Similarly, the energies delivered to the second and third rows of the sets are proportional to the bit-2 and bit-4, respectively. Energy delivered to the pixels in the fourth row is proportional to the sum of the energies of the bit-3, bit-1, and bit-0. Three more frames are necessary to ensure that the energy delivered to all the pixels in the display is proportional to the sum of the energies corresponding to all the bits of the gray shade data. Hence, $(8N)$ time intervals are necessary to complete a cycle. The orthogonal matrix in (8) and the corresponding matrix in (9) are rotated three times (row wise) and the scanning is performed so that the three additional frames will complete a cycle. For example, rotating the matrix down once will ensure that the first row of each set of the scanning lines will get energy that is proportional to the sum of the energies of bit-3, bit-1, and bit-0. Energies delivered to the second, third, and fourth lines in each set of scanning lines will be proportional to that of the bit-5, bit-2, and bit-4, respectively. Orthogonal matrices for the second, third and the fourth frames and their corresponding data matrices are given in (14)-(19).

$$O(2)_{4\times8}=\begin{bmatrix}+2&+1&+4&-1&-2&-1&-4&+1\\+4&-4&+4&-4&+4&-4&+4&-4\\+2&0&-2&0&+2&0&-2&0\\0&+4&0&-4&0&+4&0&-4\end{bmatrix} \quad (14)$$

$$D(2)_{4\times8}=\begin{bmatrix}d_1&d_0&d_3&d_0&d_1&d_0&d_3&d_0\\d_5&d_5&d_5&d_5&d_5&d_5&d_5&d_5\\d_2&0&d_2&0&d_2&0&d_2&0\\0&d_4&0&d_4&0&d_4&0&d_4\end{bmatrix} \quad (15)$$

$$O(3)_{4\times8}=\begin{bmatrix}0&+4&0&-4&0&+4&0&-4\\+2&+1&+4&-1&-2&-1&-4&+1\\+4&-4&+4&-4&+4&-4&+4&-4\\+2&0&-2&0&+2&0&-2&0\end{bmatrix} \quad (16)$$

$$D(3)_{4\times8}=\begin{bmatrix}0&d_4&0&d_4&0&d_4&0&d_4\\d_1&d_0&d_3&d_0&d_1&d_0&d_3&d_0\\d_5&d_5&d_5&d_5&d_5&d_5&d_5&d_5\\d_2&0&d_2&0&d_2&0&d_2&0\end{bmatrix} \quad (17)$$

$$O(4)_{4\times8}=\begin{bmatrix}+2&0&-2&0&+2&0&-2&0\\0&+4&0&-4&0&+4&0&-4\\+2&+1&+4&-1&-2&-1&-4&+1\\+4&-4&+4&-4&+4&-4&+4&-4\end{bmatrix} \quad (18)$$

$$D(4)_{4\times8}=\begin{bmatrix}d_2&0&d_2&0&d_2&0&d_2&0\\0&d_4&0&d_4&0&d_4&0&d_4\\d_1&d_0&d_3&d_0&d_1&d_0&d_3&d_0\\d_5&d_5&d_5&d_5&d_5&d_5&d_5&d_5\end{bmatrix}. \quad (19)$$

In summary, a cycle is complete when all the set of scanning electrodes are selected with all the select vectors in the orthogonal matrices of (8), (14), (16), and (18) once. Typical wave-

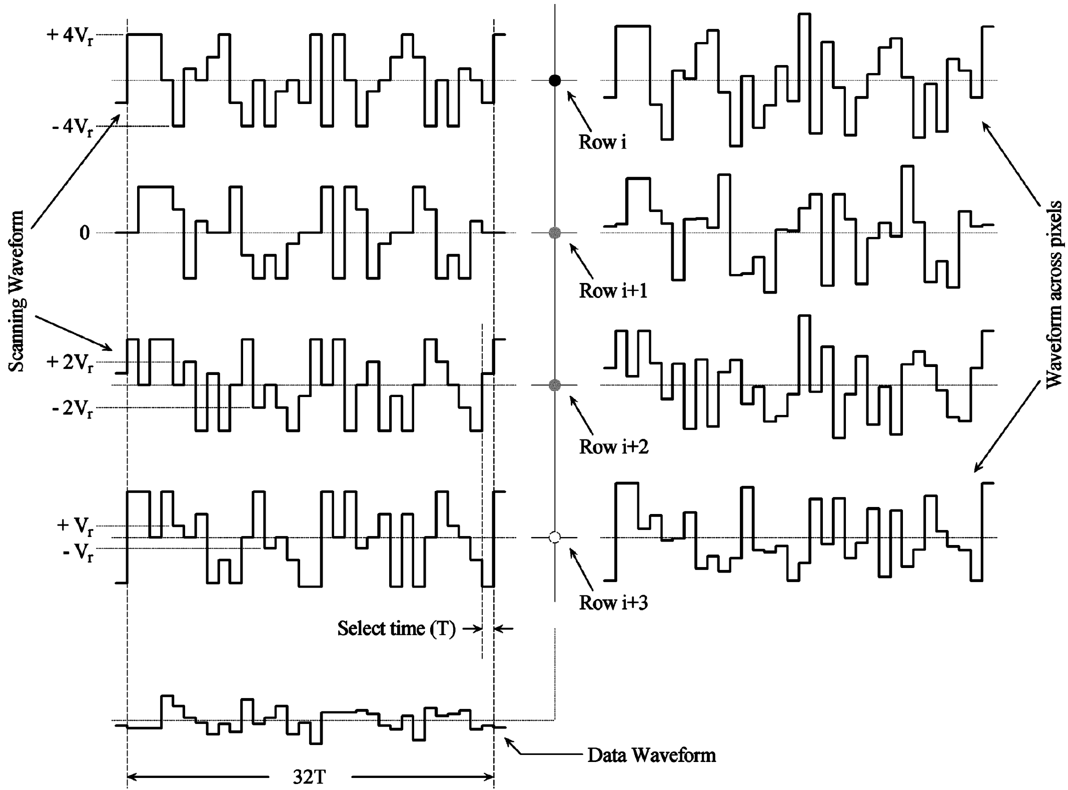


Fig. 1. Typical waveforms when the scanning of the matrix display is based on integer wavelets. Scanning (row) waveforms have seven voltage levels and the data waveforms have 18 voltages.

forms based on the orthogonal matrix in (10) are shown in Fig. 1. Each select vector in (10) is rotated to obtain three other select vectors. The waveforms across the pixels are DC free because the wavelets in these orthogonal matrices are DC free.

III. Analysis

The rms voltage across pixels in the display when the display is scanned with waveforms derived from wavelets is as follows:

$$V_{\text{pixel}}(\text{RMS}) = \sqrt{\frac{4\sum_{k=0}^{5} 2^k (V_r^2 - 2.d_{k,i,j} V_r.V_c + N.V_c^2)}{8N}} \tag{20}$$

$$V_{\text{ON}}(\text{RMS}) = \sqrt{\frac{63\,(V_r^2 + 2V_r.V_c + N.V_c^2)}{2N}} \tag{21}$$

$$V_{\text{OFF}}(\text{RMS}) = \sqrt{\frac{63\,(V_r^2 - 2V_r.V_c + N.V_c^2)}{2N}} \tag{22}$$

The selection ratio, defined as the ratio of RMS voltage across the ON pixels to that across OFF pixels is a maximum when

$$\frac{V_r}{V_c} = \sqrt{N} \tag{23}$$

and the maximum selection ratio is

$$\frac{\text{V}_{\text{ON}}}{\text{V}_{\text{OFF}}} = \sqrt{\frac{\sqrt{N}+1}{\sqrt{N}-1}}. \tag{24}$$

It is the maximum selection ratio that is attainable by any addressing technique for driving passive matrix LCDs. Selection ratio is a measure of the discrimination that can be achieved between ON and OFF pixels and a higher selection ratio will ensure good contrast in the display. The OFF pixels in the display are biased near the threshold voltage of the LCD and the supply voltage of the drive electronics is obtained by equating the expression for the voltage across OFF pixels to the threshold voltage of the LCD

$$V_{\text{OFF}} = \sqrt{\frac{63(2N - 2\sqrt{N})}{2N}}.V_c = V_{\text{threshold}}. \tag{25}$$

Hence,

$$V_c = \frac{V_{\text{threshold}}}{\sqrt{63\left(1 - \frac{1}{\sqrt{N}}\right)}}. \tag{26}$$

Supply voltage is determined by the maximum swing in the addressing waveforms. Maximum amplitude of the scanning waveforms is small as compared to that of the data voltages when N is small. It is higher than the maximum amplitude of the data voltages when N is large. Hence, the supply voltage is defined for two ranges of N. Maximum swing in the data waveform is also dependent on the orthogonal matrix. For example, the maximum amplitude is $10V_c$ when the orthogonal matrix in (8) is used where as it is $12V_c$ when the matrix in (10) is used.

Supply voltage when orthogonal matrix in (8) is used for scanning the display is

$$V_{s(8)} = \begin{cases} 20V_c & \forall \quad N \leq 6 \\ 8\sqrt{N}V_c & \forall \quad N > 6 \end{cases}. \tag{27}$$

The supply voltage when matrix of (10) is used for scanning the display is given in (28) as

$$V_{s(10)} = \begin{cases} 24V_c & \forall \quad N \leq 9 \\ 8\sqrt{N}V_c & \forall \quad N \geq 9 \end{cases} \tag{28}$$

$$\text{Supply voltage}_{(N\geq 9)} = 8.V_r = 8\sqrt{N}V_c = \frac{8\sqrt{N}V_{\text{threshold}}}{\sqrt{63\left(1-\frac{1}{\sqrt{N}}\right)}}. \tag{29}$$

The analysis presented in the previous section is independent of the scanning sequence, the order in which the scanning electrodes are selected with select vectors. There are $32!$ ways of selecting a set of four electrodes with the thirty-two select vectors and the $(N/4)$ sets of scanning electrodes themselves may be selected in $(N/4)!$ ways. The rms voltage across the pixel will not change with the scanning sequence but the frequency spectrum across the pixels and the power consumption of the display will depend on the scanning sequence [5].

IV. Drive Electronics

The techniques to reduce the hardware complexity of the drive electronics are outlined in this section.

A. Reducing the Hardware Complexity

1) Row (Scan) Drivers: The number of voltages in the scanning waveforms is seven, viz., $\pm 4V_r$; $\pm 2V_r$; $\pm V_r$ and 0. Data drivers that are capable of applying any one of the eight voltages to each electrode may be used. They consist of an 8:1 analog multiplexer, a 3-bit latch and 3-bit shift register in each stage that corresponds to one output of the driver. However, by considering the fact that just four voltages are necessary (three select voltages and a non-select voltage), it is adequate to have a 4:1 analog multiplexer, 2-bit latch, and 2-bit shift register in each stage of the display driver along with four 8:1 analog multiplexers that are common to all the row drivers in the display. The hardware reduction achieved in each stage of the driver contributes to a large reduction in the hardware complexity because the number of stages in the drivers is equal to N, the number of scanning electrodes in a display and N is usually large. Hence, the reduction in hardware is significant while the increase in hardware (four 8:1 multiplexers) to achieve this reduction is negligible. Schematic diagram of a simplified row drive circuit is shown in Fig. 2.

2) Column (Data) Drivers: Number of voltages in the data waveforms is either 17 or 18 depending on the selection of the matrix ((8) or (10)) for scanning the display. Hence, each stage of the column driver should have a (17:1) or a (18:1) analog multiplexer, a 5-bit latch to hold the value of the column data during the select time and a 5-bit shift register so that the column data can be serially shifted in to the driver. Here again the number of voltages that are necessary at a given instant of time is just four to eight depending on the select vector. Hence, LCD drivers that are capable of applying just eight voltage levels (with an 8:1 analog multiplexer, 3-bit latch and 3-bit shift register for each output) are adequate and the increase in hardware complexity due to the addition of eight 4:1 analog multiplexers that are common to all the stages in the driver is negligible because the number of data (column) electrodes is usually large. External multiplexers for the data drivers are shown in the Fig. 3.

3) Controller: Gray shade data of the pixels in a matrix display is stored in the buffer memory as a one-dimensional array

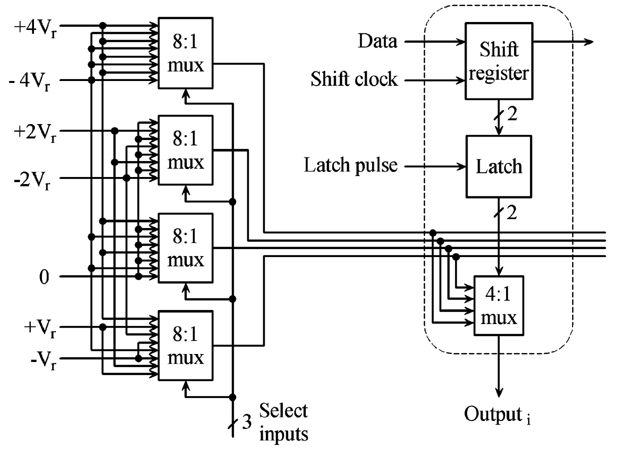


Fig. 2. The fact that just four voltages are necessary at a given instant of time is used to reduce the hardware complexity of the row drivers. A 2-bit shift register, 2-bit latch and a 4:1 analog multiplexer are adequate when four (8:1) analog multiplexers are common to all stages of the row drivers (one per each address line) as compared to a 3-bit shift register, 3-bit latch and 8:1 analog multiplexers that are necessary for each output of the row drivers.

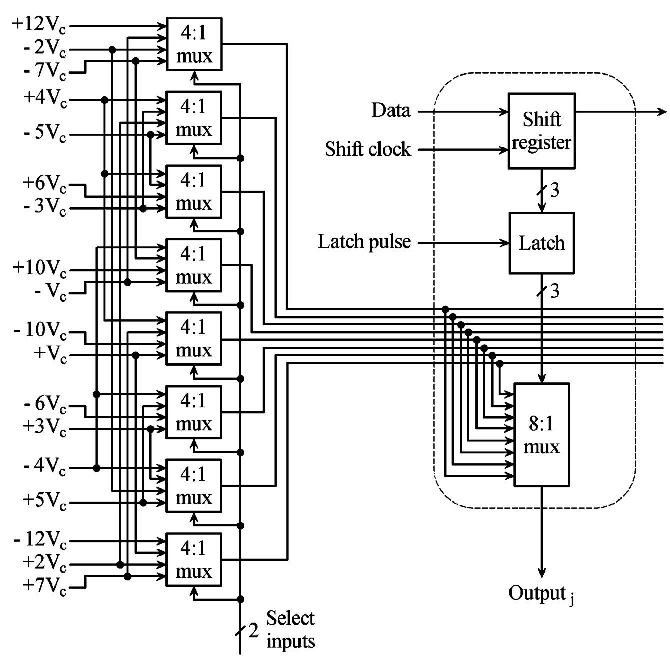
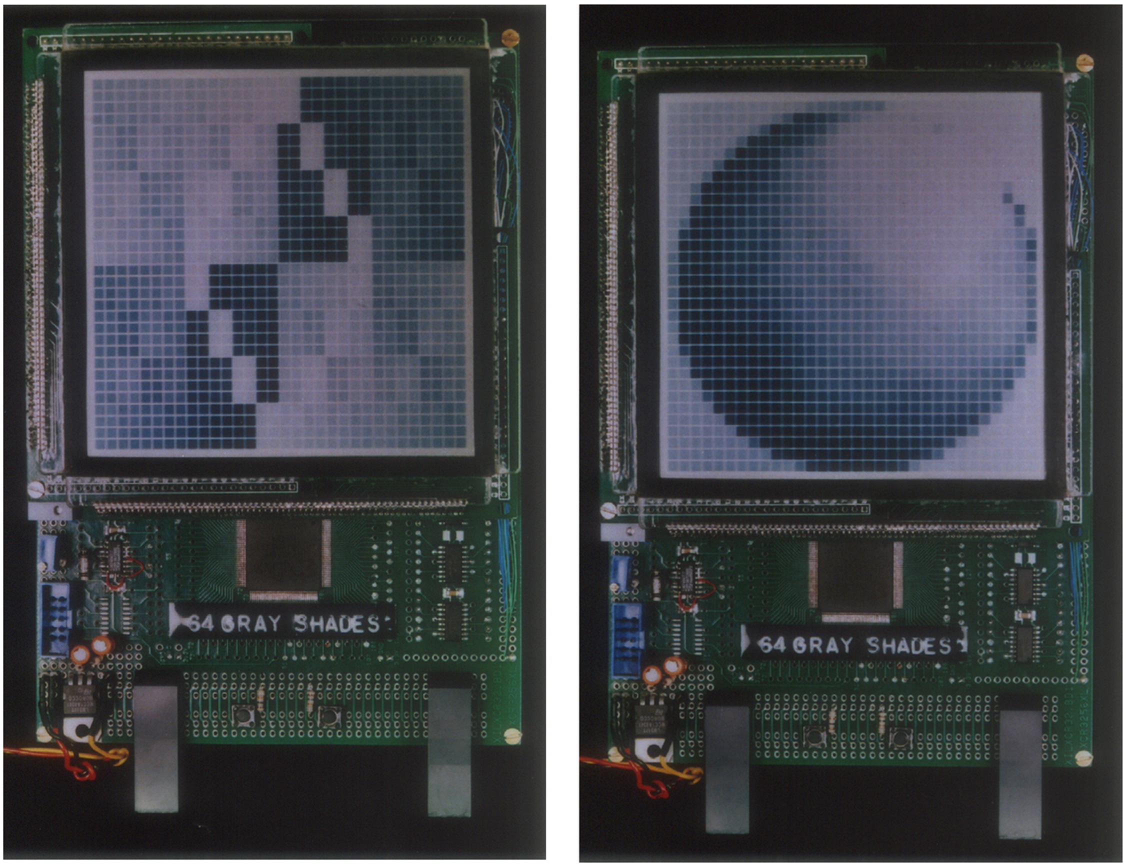


Fig. 3. The fact that just eight voltages or less are necessary at a given instant of time is used to reduce the hardware complexity of the column drivers. A 3-bit shift register, 3-bit latch and an 8:1 analog multiplexer are adequate when eight (4:1) analog multiplexers are shared by all the stages of the column drivers as compared to having a 5-bit shift register, a 5-bit latch and a (18:1) analog multiplexer for each output stage of the column (data) drivers.



(a) (b)

Fig. 4. (a) Photograph of the prototype: (a) with 64 gray shades being displayed using integer wavelets and (b) capable of displaying 64 gray shades using integer wavelets. (Color version available online at: http://ieeexplore.ieee.org.)

and the address of a pixel in ‘row-i’ and ‘column-j’ is computed as follows.

$$\text{Address} = (i-1).M + j - 1. \tag{30}$$

Address of the four pixels in each column has to be generated repeatedly and a simple binary counter can be used provided the number of memory locations allocated for each row is an integer power of two and the number of electrodes that are in a set is also an integer power of two. We have avoided the computation of the address by having four rows in a set and a binary counter can be used to generate the address without any multiplication and addition.

B. Implementation

The orthogonal matrix in (10) is used to scan a 32×32 twisted nematic matrix display. The number of voltages in the data waveform is 18 instead of the 17 for the matrix in (8). However, this does not change the hardware complexity of the data drivers because we have used drivers that are capable of applying 1 out of 8 voltages. The controller is implemented in a CPLD (XCR 3256 XL) with 84 macro-cells, 181 product terms, and 55 registers. Photograph of the prototype is shown in Fig. 4. Typical row (scanning) and column (data) waveforms are shown in Fig. 5. Typical waveform across a pixel is shown in Fig. 6.

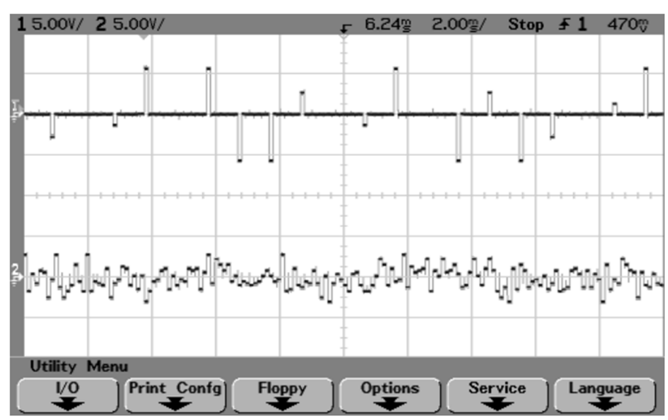


Fig. 5. Typical row (scanning) and column (data) waveforms when 64 gray shades are displayed in a 32×32 matrix LCD. Just half a cycle has been captured on the screen for the sake of clarity.

V. Comparison

Most of the techniques that were proposed by various researchers during the last century were primarily for displaying bilevel images. Number of time intervals to complete a cycle increases when frame modulation or pulsewidth modulation are employed to display gray shades. Number of time intervals in a cycle is $(126N)$ when 64 gray shades are displayed using frame or pulse width modulation. The number of time intervals in a

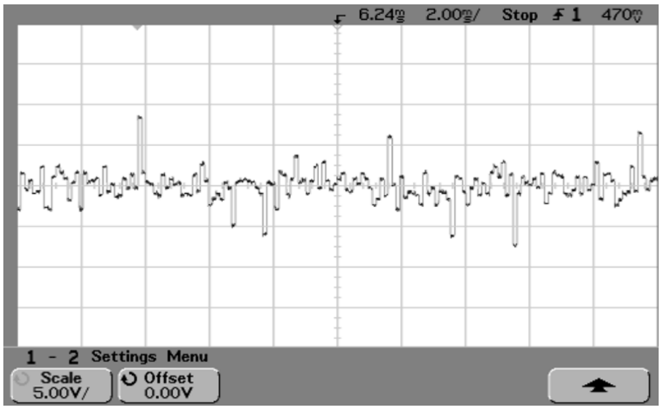


Fig. 6. Typical waveform across a pixel (row waveform minus the column waveform) in the prototype of the display capable of displaying 64 gray shades.

cycle includes polarity inversion to achieve DC-free waveforms across the pixels. Number of time intervals for all the techniques in this comparison is the minimum number of time intervals to achieve DC-free operation. On the other hand, number of voltages in the drive waveforms increases when amplitude modulation or pulse height modulation [6] is used along with line-by-line and multi-line addressing techniques. Amplitude modulation will have 126 voltages in the column waveforms, 3 voltages in the scanning waveforms and it needs $4N$ time intervals to complete a cycle. A gray shade technique that is based on multiordered orthogonal matrix which was proposed by Young *et al.* [7] can display a large number of gray shades with less time intervals but the number of voltages in the data waveforms will be large. For example, 35 voltages in the data waveforms are necessary to display 64 gray shades although the number of voltages in scanning waveforms (just 3) and the number of time intervals to complete a cycle ($12N$) are small. It is not possible to reduce the hardware complexity of the drive electronics if amplitude modulation, pulse height modulation [6] and the technique based on multiordered orthogonal matrices [7] are used for displaying a large number of gray shades. Number of time intervals to complete a cycle will be too large if paraunitary matrices are used to display a large number of gray shades. It may be more appropriate to compare the wavelet-based technique with the successive approximation techniques [2], [8] since both the techniques are based on delivering energies that are proportional to the bit weight of the gray shade data in several time intervals. A comparison of the wavelet based technique with successive approximation techniques based on line-by-line addressing and multi-line addressing is given in Table I.

The number of rows is chosen to be four in case of multi-line addressing. The number of time intervals to complete a cycle is less for the wavelet based technique and hence the display can be scanned at a lower rate as compared to the successive approximation technique when all other parameters are equal. Slow scanning is helpful to reduce the power consumption. The brightness nonuniformity of pixels due to distortion in the addressing waveforms will also be less because the select time is larger when the number of time intervals is small. A lower supply voltage of the wavelet-based technique is advantageous in portable devices. Supply voltage of the wavelet-based technique is compared with that of the successive approximation

TABLE I
COMPARISON OF THE GRAY SHADE TECHNIQUES (64 GRAY SHADES)

Parameter	Successive approximation technique (Line-by-line)	Successive approximation (MLA) 4 lines in a subgroup	Wavelet based technique 4 electrodes in a set
Number of time intervals for 64 gray shades	12N	12N	8N
Supply voltage	High (100%)*	Intermediate (50%)	Low (40.8%)
Number of voltages in scanning waveforms	13 (19 for IAPT)	13	7
Number of voltages in the data waveforms	12 (19 for IAPT)	17	17

* Supply voltage as a ratio is given as compared to Successive approximation (line-by-line technique). Number is valid for N>16 in case of SA-MLA and N>9 in case of Wavelet based technique.

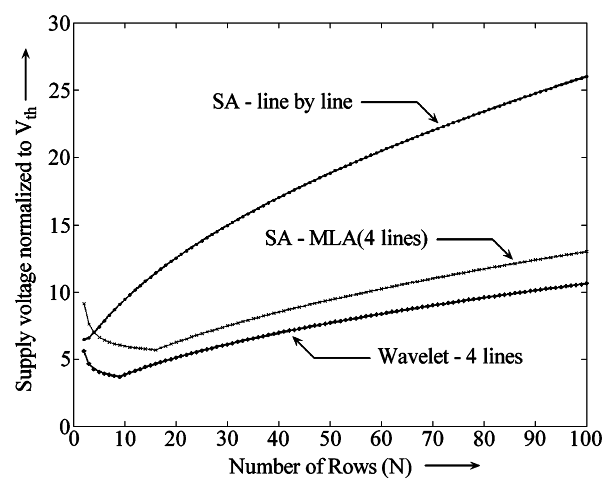


Fig. 7. A plot of supply voltage verses number of scanning electrodes to compare the successive approximation and wavelet-based techniques. Supply voltage for the wavelet-based technique is plotted using the expression in (28).

techniques [2], [8] in Fig. 7. Response of the display for different gray shades was measured using a cell (3.9 μm) filled with RO-TN 403 (liquid crystal mixture) when 32 rows are scanned with waveforms derived from the orthogonal matrix in (10). The refresh rate is 50 Hz. Tables II and III show the response times in milliseconds when the pixels are switched from one gray shade to another using the wavelet based technique. Rise time and fall times are measured from 10% to 90% change in transmission of the difference in transmission between two states. The upper triangle in this table shows the rise times and the lower triangle gives the fall times. Response of the cell was also measured when it is switched to ON and OFF states using voltages under multiplexed condition, by applying square waveforms with RMS voltage equal to V_{ON} (1.58 V) and V_{OFF} (1.33

TABLE II
RESPONSE TIMES (IN MILLISECONDS) WHEN PIXELS ARE SWITCHED TO DIFFERENT GRAY SHADES USING WAVELETS ($V_{supply} = 8.78$ V)

Gray shade value	0 (OFF)	3	7	11	15	19	23	27	31	35	39	43	47	51	55	59	63 (ON)
0 (OFF)	-	124	118	118	114	105	102	98	95	92	96	90	88	87	85	78	74
3	96	-	120	112	114	100	96	91	88	85	82	82	80	74	73	71	70
7	92	100	-	120	116	100	97	93	90	88	83	86	87	85	80	70	68
11	90	98	99	-	118	112	102	98	96	90	94	88	84	80	76	72	66
15	85	90	92	104	-	115	110	101	97	95	90	93	90	82	79	74	71
19	79	86	88	100	105	-	116	112	106	100	93	94	90	84	80	74	73
23	70	79	84	94	98	104	-	114	115	108	98	95	92	85	81	76	75
27	70	72	78	92	93	98	108	-	122	120	116	99	94	87	83	77	76
31	67	70	75	88	91	96	100	110	-	126	112	104	98	89	86	82	82
35	65	77	78	89	88	92	96	104	110	-	120	112	102	96	93	88	86
39	62	72	74	85	86	87	88	106	100	108	-	119	116	107	103	92	88
43	68	70	75	80	80	84	85	88	90	103	114	-	113	109	106	97	89
47	62	64	70	76	80	78	82	83	86	90	98	104	-	115	108	101	93
51	62	64	70	74	78	79	76	75	84	82	96	100	104	-	114	98	95
55	55	65	71	78	76	77	69	74	82	78	92	95	101	107	-	116	105
59	50	68	65	74	75	70	66	72	80	74	86	84	94	92	102	-	118
63 (ON)	58	65	60	72	77	72	68	70	76	69	75	80	88	91	95	108	-

Upper triangle in the table gives the rise time and the lower triangle of the table gives the fall time when the pixels when they are switched from one gray shade to another.
Rise time and fall times are measured from 10% to 90% change in transmission of the difference in transmission between two states.

TABLE III
RESPONSE TIMES (IN MILLISECONDS) WHEN PIXELS ARE SWITCHED TO DIFFERENT GRAY SHADES USING WAVELETS ($V_{supply} = 8.36$ V)

Gray shade value	0 (OFF)	3	7	11	15	19	23	27	31	35	39	43	47	51	55	59	63 (ON)
0 (OFF)	-	132	130	121	125	120	116	110	106	102	95	94	80	86	85	77	66
3	58	-	138	130	124	118	114	115	116	114	110	106	94	88	82	78	74
7	60	80	-	130	128	125	120	116	106	100	100	103	100	94	90	82	79
11	52	72	96	-	129	124	120	118	115	108	104	110	108	95	93	86	84
15	56	68	90	100	-	122	116	120	115	112	110	114	110	104	96	88	86
19	60	70	80	92	108	-	128	124	122	116	110	100	100	88	86	74	78
23	48	65	72	88	104	116	-	128	115	118	108	116	112	106	102	92	90
27	62	67	70	90	96	110	116	-	132	128	114	110	96	84	88	86	80
31	55	65	66	90	93	98	110	120	-	130	126	115	106	108	102	90	88
35	51	68	67	88	89	95	110	120	123	-	128	110	104	96	94	85	84
39	58	66	71	78	86	84	104	108	120	116	-	132	113	98	95	87	86
43	60	65	70	80	84	85	102	98	100	95	120	-	124	116	100	88	90
47	50	65	72	78	84	80	95	82	94	88	100	111	-	120	116	96	92
51	50	60	60	70	80	83	94	84	92	75	89	88	112	-	125	110	92
55	55	56	58	70	80	82	90	82	88	72	88	80	110	118	-	115	100
59	49	56	60	66	77	73	80	78	84	70	76	73	92	96	100	-	118
63 (ON)	47	48	60	66	74	70	66	74	80	75	70	73	82	90	90	110	-

volts, the threshold of the liquid crystal mixture) for the sake of comparison. Switch ON (rise) and switch OFF (fall) times were 53 and 34 ms, respectively. The cell is not optimized for fast response. From the Tables II and III it is evident that the response times are slightly higher under multiplexed condition when the pixels are switched from one extreme to the other extreme state (i.e., ON and OFF). However, the gray scale to gray scale switching can be high by a factor of about 2.5 in some cases, when 32 lines are multiplexed.

VI. Conclusion

Salient features of the wavelet-based techniques are as follows. Amplitude and the number of time intervals in the wavelets are selected with an aim to reduce the supply voltage of the drive electronics.

1) A compact orthogonal matrix is constructed to reduce the number of time intervals in a cycle.
2) Number of nonzero elements in the select vector is chosen to reduce the hardware complexity of the drivers.
3) Number of nonzero elements in the select vector may also be used to match the drivers on a given display panel.
4) Number of rows in the orthogonal matrix can be chosen to be an integer power of two to reduce the hardware complexity of the controller.

These features are unique to the wavelet-based technique and hence they have several advantages as compared to the conventional techniques for displaying gray shades.

References

[1] T. N. Ruckmongathan, "Addressing techniques for RMS responding LCDs—A review," in *Proc. Jpn. Display '92*, 1992, pp. 77–80.

[2] K. G. Panikumar and T. N. Ruckmongathan, "Displaying gray shades in passive matrix LCDs using successive approximation," in *Proc. 7th Asian Symp. on Inf. Display (ASID-2002)*, 2002, pp. 229–232.

[3] T. N. Ruckmongathan, P. Nanditha Rao, and A. Prasad, "Wavelets for displaying gray shades in LCDs," in *2005 Soc. Inf. Display Int. Symp. Dig. Tech. Papers*, pp. 168–171.

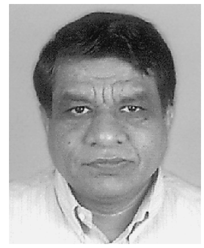
[4] T. N. Ruckmongathan, "Displaying gray shades in liquid crystal displays," *Pramana*, vol. 61, no. 2, pp. 313–329, 2003.

[5] T. N. Ruckmongathan, M. Govind, and G. Deepak, "Reducing power consumption in passive matrix liquid crystal displays," *IEEE Trans. Electron Devices*, vol. 53, no. 7, pp. 1559–1566, Jul. 2006.

[6] A. R. Conner and T. J. Scheffer, "Pulse height modulation gray shading methods for passive matrix LCDs," in *Proc. 12th Int. Display Res. Conf. (Jpn. Display'92)*, pp. 69–72.

[7] S. Young, J. Lee, B. Lam, J. Ng, and I. Tsoi, "Gray-scale addressing method by multi-order paraunitary/orthogonal building blocks," *J. SID 8/4*, pp. 283–288, 2000.

[8] T. N. Ruckmongathan, "A successive approximation technique for displaying gray shades in liquid crystal displays (LCDs)," *IEEE Trans. Image Process.*, Paper TIP-2176–2006, accepted for publication.



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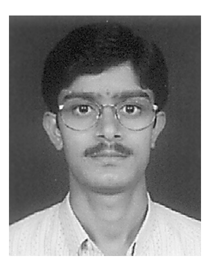

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