S3-5 Pulse-Height Modulation (PHM) Gray Shading Methods for Passive Matrix LCDs

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Abstract

We developed a pulse height modulation (PHM) gray shading technique for passive matrix LCDs which provides unlimited gray shades even for fast-responding types, and overcomes the difficulties of conventional pulse-width and frame modulation gray shading. The theory of this method will be presented along with examples for standard LCD addressing and active addressing [1] drive techniques.

Introduction

Gray levels have become indispensable in presenting information on liquid crystal displays. However, the two known methods to achieve gray levels in passive matrix LCDs have failed to meet expectations in the latest generation of "notebook" computers and other products. The most commonly used gray scale method, known as frame modulation [2], causes objectionable "swim" and flicker in gray-shaded pixels when faster-responding LCDs are employed. Yet these faster-responding displays are a requirement in any computer with a so-called "graphical" user interface. The other gray scale method, known as pulse-width modulation (PWM) [3], has difficulty in producing even 16 distinct gray levels; this is plainly inadequate for "multimedia" applications where desirably 256 gray levels are required to bring out the fine detail of the pictures.

The objective of this work is to provide a means to address passive matrix LCDs, especially relatively fast responding ones, such that an unlimited number of gray levels may be provided on the display. We accomplish this with a new gray level method we call PHM where many different voltage levels are applied to the display column instead of just the two levels of the known gray level schemes.

Pulse Height Modulation (PHM)

Previously it was thought that the data voltages applied to the display column had to be either +F or −F throughout the entire frame time in order to independently supply the correct root-mean-square (RMS) voltages to the pixels in a multiplexed display. However, we found that we could relax this condition, allowing many voltage levels on the display column, and still keep each pixel's RMS average voltage correct in order to portray the desired gray level. We first considered the simple amplitude modulation (AM) that is used to provide gray levels in TFT displays. However AM did not satisfy the special RMS average condition for a passive matrix because the column electrode supplies voltages to all the pixels in that column, not just one as in the case of a TFT LCD. We then considered PHM approaches and found them to be suitable for passive matrices. One approach, called the "split-interval" method, maintains the correct RMS level in the pixel waveform averaged *over each row address time interval* (and consequently over the whole frame). The other approach, which we call the "full-interval" method, maintains the correct RMS level in the pixel waveform when averaged *over the whole frame period.* This paper will describe the principles of these two approaches; various hardware implementations of PHM will be described elsewhere [4].

Split-interval method

Application to standard addressing

We first consider the split-interval method, starting with a review the pulse-width modulated gray scale method. Fig. 1 shows a portion of a pulse-width modulated column signal with a row signal and corresponding pixel difference voltage for an N row display . For a gray level corresponding to a certain fraction "f" of an "on" pixel level, a column voltage of −F (of opposite polarity to the row strobe pulse S) is applied only for a certain fraction "f" of the row select time interval Δt, and +F, corresponding to an "off" pixel, is applied for the remaining fraction. Over the remaining N−1 time intervals of the frame period the pixel voltage is either +F or −F.

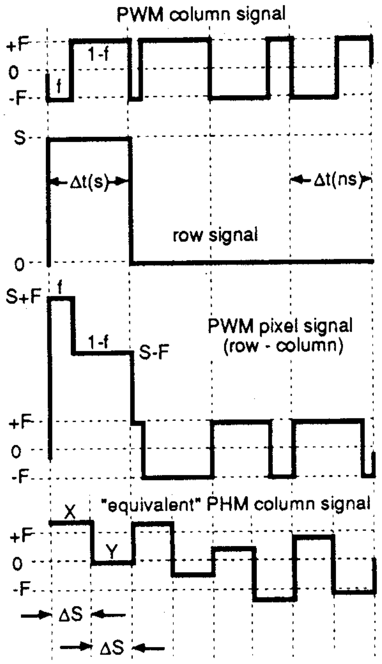

Figure 1. Application of the split-interval PHM gray level method to standard LCD drive. Example shows portions of a pulse-width modulated column signal (top) compared with a pulse-height-modulated column signal (bottom) giving the same gray level value at the pixel.

The RMS voltage appearing across the pixel during the row select time interval Δt(s) is therefore:

$$\langle U_{\Delta t(s)}\rangle = \sqrt{f(S+F)^2+(1-f)(S-F)^2} \qquad [1]$$

and for the N−1 remaining, non-selected time intervals Δt(ns) of the frame period :

$$\langle U_{\Delta t(ns)}\rangle = F \qquad [2]$$

The basis for split-interval PHM lies in replacing the two fixed levels, which vary in width, with two variable voltage levels which have fixed, equal pulse widths. In this way the resulting frequencies of the column voltage waveforms are independent of the number of gray levels, unlike standard PWM where the column drive frequencies are increased by a factor of (2^n-1), where n is the number of bits of gray scale. With standard PWM "rounding-off" of the drive waveforms caused by the RC filter action of the panel precludes more than about 8 levels of gray.

In the split-interval PWM method the time intervals Δt are divided into two equal subintervals, Δs, and a different column voltage, X and Y, is applied over each subinterval to give the same RMS pixel voltages $\langle U_{\Delta t(s)}\rangle$ and $\langle U_{\Delta t(ns)}\rangle$ of eqs. 1-2. With two equations and two unknowns we solve for X and Y as follows:

$$X = F\left(1-2f+2\sqrt{f(1-f)}\right) \qquad [3]$$
$$Y = F\left(1-2f-2\sqrt{f(1-f)}\right)$$

Eqs. 3 are illustrated in graphical form in Fig. 2, which shows the normalized pulse heights X/F and Y/F plotted as a function of the gray level fraction f. Reading from Fig. 2, there are generally two unique voltage levels, X and Y, for every gray level fraction f.

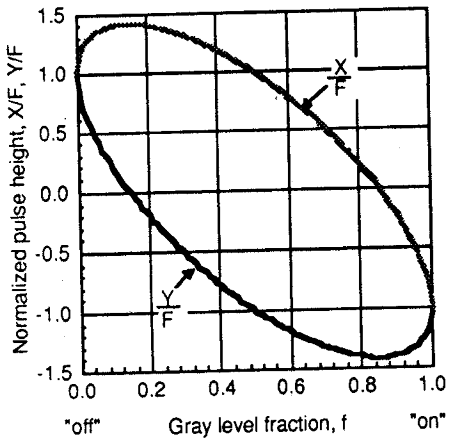

Figure 2. Normalized pulse heights X/F, Y/F as a function of gray level fraction f according to eq. 3 for the split-interval gray level method.

The PHM gray level method requires many different column voltage levels and so implementation of this method requires multilevel, TFT-type column drivers. The appropriate X,Y voltage levels given by eq. 3 could be set by a resistor ladder, or perhaps a square root computation if a large number of levels (>256) were required. Depending on the actual column drivers utilized, precalculated values of X and Y based on eq. 3 could be provided from a look-up ROM.

Applications to active addressing

Standard LCD addressing techniques become unsuitable when the liquid crystal display response times are made fast enough to achieve video rates. A new drive method, known as active addressing, was recently introduced for these types of displays [1]. Frame modulation, also known as frame-rate control (FRC) is particularly unsuitable to achieve gray levels with fast responding display cells because of flicker, noise and "swim" effects. However a type of pulse-width modulation, illustrated in Fig. 3, can be used, although this suffers from the same high frequency problems of standard PWM. We therefore wondered if split-interval PHM could be applied to active addressing as well.

Indeed, we were able to successfully apply the split-interval PHM gray scale method to active addressing for the case of bi-level and tri-level row waveforms. In fact, these gray levels are almost obtained "for free" because multi-level column drivers are required for implementations of active addressing in any case. Fig. 3 shows one time interval of an active addressing column signal using PWM with 4 bits of gray scale. The time interval is subdivided into four unequal subintervals of length ratio 1:2:4:8 with the four voltage levels A, B, C and D, computed for each bit-plane of the information vector [4], applied in turn. The voltage A corresponds to the least significant gray bit (LSB) and D corresponds to the most significant gray bit (MSB). There are of course many such time intervals in the frame period of the column signal, each one generally having a different set of voltage levels.

As before, the time interval is split into two equal subintervals and two voltages levels X and Y are applied such that the RMS pixel voltage averaged over one full time interval is the same value as for the case of PWM. For the case where the row voltages are either bi-level or tri-level the resulting values of X and Y are given by:

$$X=\frac{1}{2}\left[p+\sqrt{2q+p^2}\,\right] \qquad [4]$$
$$Y=\frac{1}{2}\left[p-\sqrt{2q-p^2}\,\right]$$

where p and q are related to A,B,C and D by:

$$p=\frac{2}{15}[A+2B+4C+8D] \qquad . \qquad [5]$$
$$q=\frac{2}{15}\left[A^2+2B^2+4C^2+8D^2\right] \qquad .$$

The above equations can easily be extended to include more gray bit-planes, providing more gray levels.

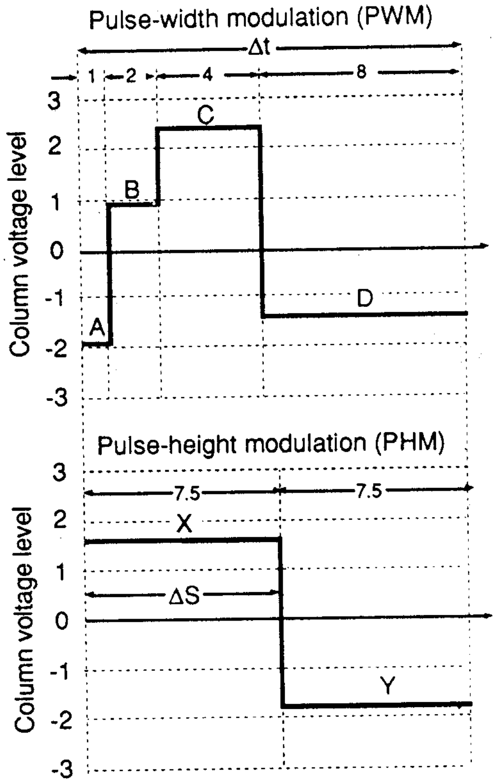

Figure 3. Example of split-interval PHM gray level scheme applied to active addressing. PWM column signal (upper) and equivalent PHM column signal (lower) give the same pixel RMS voltage.

Following the example illustrated in Fig. 3, for A = −1.888, B = 0.944, C = 2.360 and D = −1.416 we obtain X = 1.576 and Y = −1.828. As was the case for standard addressing, the implementation of the split-interval method requires some arithmetic circuitry or a look-up table containing precalculated values of X and Y.

Referring to Fig. 3 it can be seen that for this case of 16 gray levels the narrowest pulse width in the column signal is 7.5 times wider than the narrowest pulse in the case of pulse-width modulation, resulting in 7.5 times lower frequency components in the column signal and much less waveform distortion caused by filtering by the LCD panel. For 256 gray levels, the PHM drive frequencies would be 127.5 times lower than the PWM drive frequencies! Clearly PWM would not work in this case.

Full-Interval method

We now consider the full-interval PHM method, returning first to the fundamental expressions for generalized matrix addressing [5]. Consider a liquid crystal panel of N rows and M columns. Let an information matrix I represent the desired information to be displayed on the panel, where the elements I_{ij} correspond to the desired state for the pixel on row i and column j. As before [1], we define I_{ij} = +1 for a non-select or "off" pixel and I_{ij}= −1 for a select or "on" pixel, but now we extend the derivation to include intermediate gray levels with values of I_{ij} lying on the continuum between −1 and +1.

Let each matrix row i be driven with periodic row signal $F_i(t)$ having a common period T with all the other row signals, and let each matrix column j be driven with a column signal, $G_j(t)$, also periodic over T. The voltage across a pixel, $U_{ij}(t)$, is the difference between the signals applied to row i and column j,

$$U_{ij}(t) = F_i(t) - G_j(t), \qquad [6]$$

and the root mean square value of the voltage appearing across this pixel, averaged over the frame period T; is

$$\langle U_{ij} \rangle = \frac{1}{\sqrt{T}} \sqrt{\int_0^T U_{ij}(t)^2 dt} \qquad [7]$$

Substituting eq. 6 into eq. 7 yields

$$\langle U_{ij} \rangle = \frac{1}{\sqrt{T}} \sqrt{\int_0^T F_i(t)^2 dt - 2\int_0^T F_i(t) G_j(t) dt + \int_0^T G_j(t)^2 dt} \qquad [8]$$

We now assume the row signals $F_i(t)$ are orthonormal, i.e.

$$\frac{1}{\sqrt{T}} \sqrt{\int_0^T F_j(t) F_k(t) dt} = \begin{cases} F & \text{if } j = k \\ 0 & \text{if } j \neq k \end{cases} \qquad [9]$$

Analogous to active addressing without gray levels [1], we first consider a column signal $G^*_j(t)$ that is a linear combination of all the row signals at time t:

$$G^*_j(t) = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} I_{ij} F_i(t) \qquad [10]$$

Substituting eq. 10 into eq. 8 and making use of the orthonormal condition yields the following expression for the RMS voltage across pixel ij:

$$\langle U_{ij} \rangle = F \sqrt{1 - \frac{2}{\sqrt{N}} I_{ij} + \frac{1}{N} \sum_{m=1}^{N} I_{mj}^2} \qquad [11]$$

Unfortunately, the above expression depends not only on the information element corresponding to pixel ij of interest, but to the information elements of all the other pixels in the column, making it impossible to independently address each pixel in the display. However, by introducing a special "virtual" information element and an associated "virtual row", the summation term of eq. 11 can be made constant, and thus eq. 11 made only dependent on pixel ij.

Consider now a display with N+1 rows and let the information element for the $(N+1)^{st}$ row and j^{th} column, which we will refer to as the virtual information element, be designated as $V_{(N+1)j}$. Writing the additional squared term for the $(N+1)^{st}$ row separately from the other sum, eq. 11 becomes:

$$\langle U_{ij} \rangle = F \sqrt{1 - \frac{2}{\sqrt{N}} I_{ij} + \frac{1}{N} \sum_{m=1}^{N} I_{mj}^2 + \frac{1}{N} V_{(N+1)j}^2} \qquad [12]$$

By requiring that the virtual information element $V_{(N+1)j}$ satisfies the condition:

$$V_{(N+1)j} = \sqrt{N - \sum_{m=1}^{N} I_{mj}^2}, \qquad [13]$$

eq. 12 reduces to

$$\langle U_{ij} \rangle = \sqrt{2}\, F \sqrt{1 - \frac{1}{\sqrt{N}} I_{ij}} \qquad [14]$$

which is the desired result. The gray scale RMS voltage at pixel ij now depends only on the gray scale information element for that pixel, I_{ij}, *and not on the state of any other pixel in the display.* To achieve this result an additional adjustment term must therefore be added to $G^*_j(t)$ of eq. 10, resulting in:

$$G_j(t) = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} I_{ij} F_i(t) + \frac{1}{\sqrt{N}} V_{(N+1)j} F_{N+1}(t) \qquad [15]$$

No $(N+1)^{st}$ row need be physically present on the display; only an orthonormal $(N+1)^{st}$ row signal, $F_{N+1}(t)$, must be made available from the electronic circuitry for the adjustment term. The $(N+1)^{st}$ row is thus aptly named a virtual or "phantom" row.

Where there are no intermediate gray levels present on the column, it can be seen from eq. 13 that $V_{(N+1)j} = 0$ and eq. 15 reduces to eq. 1 of reference [1]. $V_{(N+1)j}$ achieves its maximum value when the intermediate gray level corresponding to $I_{mj} = 0$ (halfway between "on" and "off") is displayed on all pixels of the column; in this case $V_{(N+1)j} = \sqrt{N} \approx 15.5$ for a display with 240 multiplexed rows. This falls outside the imposed range of $-1 \leq I_{ij} \leq +1$ specified for an information element, and thus the RMS voltage at this virtual pixel, $\langle U_{(N+1)j} \rangle$, would fall outside of the bracketed gray level range which would cause it to appear "blacker than black" or "whiter than white". However this is of no consequence since this pixel does not actually appear on the display.

The selection ratio $\langle U_{on} \rangle / \langle U_{off} \rangle$ can be obtained from solving eq. 14, for $\langle U_{on} \rangle$ with $I_{ij} = -1$ and $\langle U_{off} \rangle$ with $I_{ij} = +1$ resulting in the well-known expression

$$\frac{\langle U_{on} \rangle}{\langle U_{off} \rangle} = \sqrt{\frac{\sqrt{N} + 1}{\sqrt{N} - 1}} \qquad [16]$$

Surprisingly, including a virtual row does not decrease the optimum selection ratio, a consequence of the fact that the virtual information element cannot be chosen independently, but depends upon all the other information elements! This becomes an important consideration if many virtual rows are present [4].

Application to standard LCD addressing

Fig. 4 shows an example of the full-interval gray level method using standard LCD row addressing waveforms. The display has 6 real rows, indicated by the horizontal lines numbered 1-6, one virtual row indicated by (7), and one column electrode. The row signals are sequential block functions which have zero level everywhere except during the row select interval where the level is S. These block functions belong to an orthonormal set, obeying eq. 9, and have the RMS value of F. Thus $S = \sqrt{N} F$.

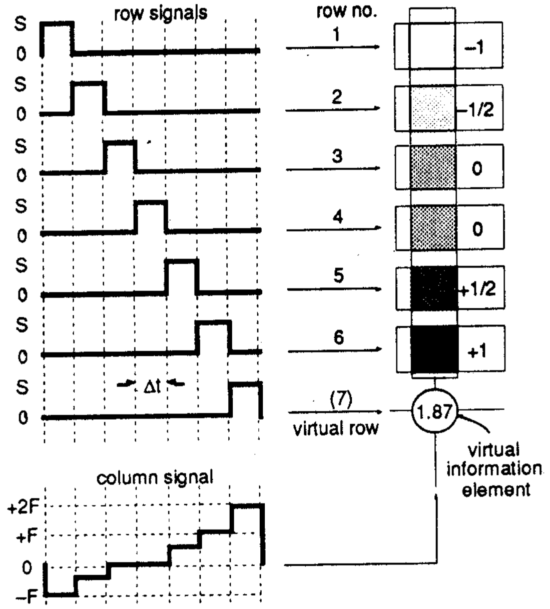

Figure 4. Full-interval PHM gray level method applied to standard LCD drive.

The intersections of the row electrodes with the column electrode define the pixels of the display. For this example we desire to present display information consisting of "off" and "on" pixels as well as intermediate gray shades lying between these two states. The desired pixel state is represented by an element of the information matrix. In this example, the information elements corresponding to the pixels of the column are, reading top to bottom, −1, −1/2, 0, 0, +1/2 and +1. In a display where "off" pixels are black and "on" pixels are white these would represent white, light gray, medium gray, medium gray, dark gray and black pixels, respectively.

Once we know the information elements for the display column we can use eq. 13 to compute the virtual information element V for that column. Using the gray levels of above example, the virtual information element is $V = \sqrt{6-2.5} = \sqrt{3.5} \approx 1.87$.

Eq. 15 is then used to generate the column signal shown in Fig. 4. The voltage levels of the column signal, normalized by F, are identical in value and sequence to the information elements of the respective columns. The last time interval in the column signal contains the "adjustment" voltage derived from the virtual information element. Note that although the virtual row is not physically present on the display its associated row signal is used in the computation of the column signal.

Application to active addressing

The full-interval, PHM example of Fig. 4 using active addressing row signals instead of standard addressing row signals is shown in Fig. 5. For simplicity we apply the second through seventh sequency-ordered Walsh functions to the six real rows and the eighth Walsh function is used in the adjustment term. The first, constant Walsh function is not used. The amplitudes of the row signals are either +F or −F, as shown in the example. These functions are orthonormal to each other and therefore obey eq. 9. In contrast to the previous example, the row function for the virtual row in this case does not involve an additional time interval. This happens because the Walsh functions are limited to finite intervals only, which is not the case for the orthogonal block pulses used in standard LCD addressing.

The virtual information element is computed from eq. 13, just as in the previous example and has the same value since the information pattern is the same.

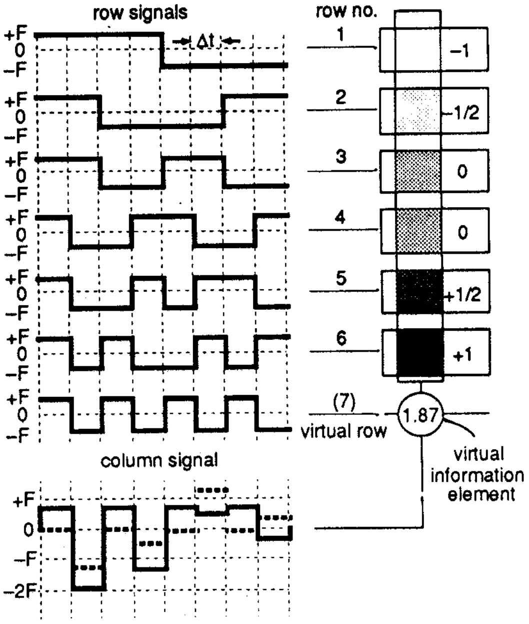

Figure 5. Full-interval PHM gray level method applied to active addressing.

The resultant column signal for the displayed gray levels computed from eq. 15 is shown in Fig. 5. Two different signals are superimposed in order to illustrate the effect of the adjustment introduced by the virtual information element. The dotted waveform indicates what the column signal would look like without the virtual row adjustment.This signal would not produce the RMS voltages across the pixels appropriate to give the correct optical states to the pixels of the column. The solid waveform includes the virtual row correction and therefore gives the proper RMS voltages across the pixels. In comparing the examples of Figs. 4 and 5 it is interesting to note that in Fig. 4 the column signal correction manifests itself as an additional time interval, whereas in Fig. 5 the correction is spread out over the existing time intervals.

Conclusion

We have established a method that is applicable to all RMS-responding passive matrix LCDs, to provide as many gray shades as desired. We have demonstrated each of the variations of PHM with actual LCDs and found the gray shades to be free of noise and other difficulties. In short, PHM can be recommended for any passive LCD requiring a large number of smooth gray shades.

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