

A gray-scale addressing technique for thin-film-transistor/liquid crystal displays

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An addressing technique allowing continuous-tone color images to be rendered on thin-film-transistor/liquid crystal displays having bilevel drivers is described. The technique uses multiple subfields per frame, with driver voltages changed synchronously with the field data. By using N bits of data per pixel, excitation is applied to the display one bit-plane per field for N consecutive fields. The technique is analyzed, its benefits and limitations discussed, and experimental results presented. Up to 16 gray levels have been demonstrated with good image quality.

Introduction

Thin-film-transistor/liquid crystal (TFT/LC) displays will become the computer displays of the '90s. They already appear in high-end portable computers and have enjoyed success in the hand-held television market in Japan. The

potential for competing successfully with the CRT in most applications exists, though early implementations of this display technology limit their applications. In this paper we discuss one shortcoming, that of limited gray scale; i.e., a picture element (pixel) typically shows fewer luminance levels than are currently available on CRTs. A solution which permits more gray levels and therefore better image rendering is described, and experimental results are presented.

TFT/LC displays may produce fewer luminance levels than desired, for several reasons. The reason addressed in this paper is that the circuits (drivers) which excite the display lack the desired amplitude resolution. This paper treats the extreme case of having binary drivers and rendering continuous-tone (contone) images, a goal that requires multiple luminance levels for satisfactory results. The developed technique has, however, obvious extensions to cases in which the driver output is quantized to more than two levels.

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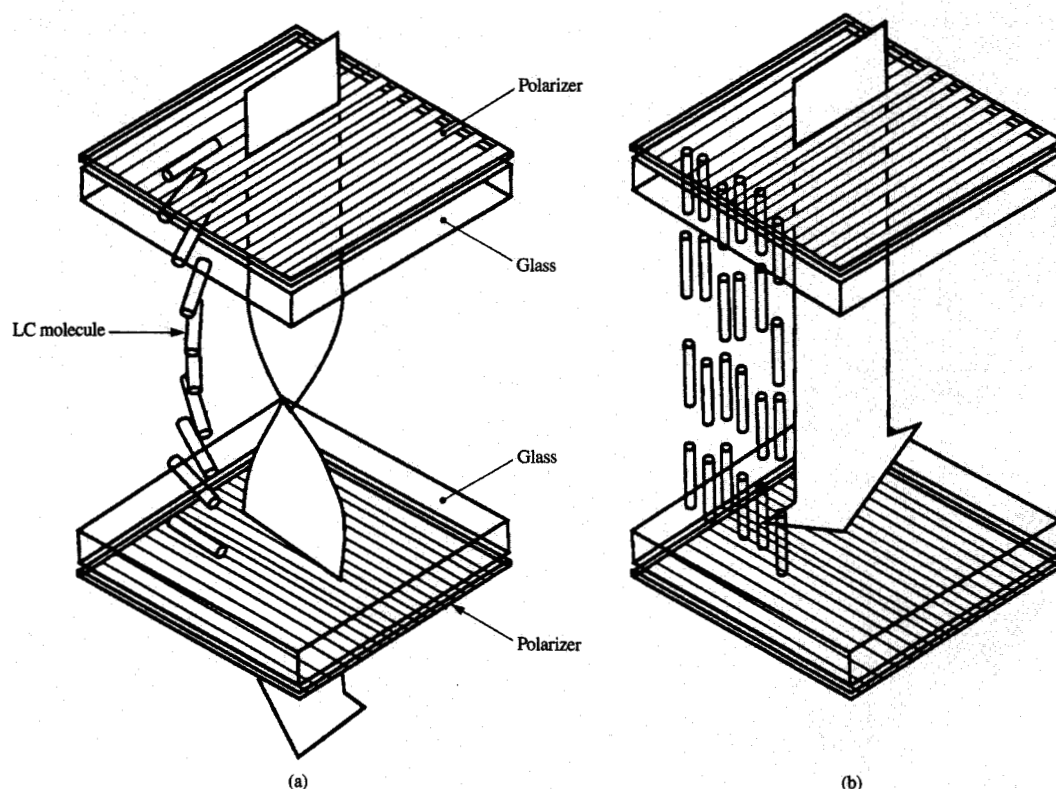


Figure 1

Idealized diagram of light propagation in a twisted nematic (TN) liquid crystal display. The unexcited state (a) obtains for zero applied electric field, and the excited state (b) occurs for voltages of approximately 5 V. The molecules at the surfaces are inclined at a small tilt not shown in the diagram.

One finds the terms “number of gray levels” and “number of colors” used interchangeably in the technical literature. In a strict sense, the terms *gray levels* or *gray shades* refer to steps in luminous intensity of a chromatically neutral light source in going from a black OFF condition to a full ON white state. This terminology was quite appropriate for describing monochrome or black-and-white television. With computer displays, a color or monochrome display may be referred to as a gray-scale display as long as its pixels show more than two levels of luminance. Color displays are designed so that equal red, green, and blue signals to a pixel produce a neutral or gray level. A three-bit-per-color TFT/LC gray-scale display shows eight intensities for each of its red, green, and blue subpixels. Taken in combination, the number of available colors is $8^3 = 512$. This is the gray-scale capability of the first TFT/LC displays to be commercially available for computer applications.

Two standards of comparison are worth mentioning. A PS/2[®] computer with a video graphics array (VGA) and a cathode ray tube (CRT) display produces 64 intensities for each of its primary colors (red, green, and blue). Thus, the total number of colors available is 262 144 or, in common terminology, 256K colors. A workstation using a CRT display and running image-rendering software has 256 intensities per primary, for a total palette of 16M colors. In these two examples, it is not the CRT display which limits the number of colors, but the system driving the display, whereas it is the TFT/LC display, not its system, that today limits the number of colors. More specifically, it is the TFT/LC data drivers which lack the required performance.

Operational TFT/LC display characteristics

Before the gray-scale technique is described, the relevant operating characteristics of the various components are

briefly discussed. We describe the liquid crystal cell operation, the excitation of the liquid crystal as controlled by the TFT array, and the drive circuits which supply signals to the TFT array.

Liquid crystal cell TFT/LC displays are first and foremost liquid crystal displays, with many of the benefits and liabilities associated with this light-modulating technology. The TFTs control the excitation seen by the liquid crystal, and thereby significantly increase the display contrast compared to the familiar simple matrix liquid crystal displays which have no controlling circuit element for each pixel. TFT/LC displays typically use the twisted nematic (TN) display effect, while most simple matrix displays use the supertwisted nematic (STN) effect. For a discussion of liquid crystals and display cell design, the reader is referred to [1].

TN liquid crystal cells operate with linear polarizers attached to the front and back of the cell. Depending on whether the two polarizers are aligned parallel or perpendicular to each other, the display will be respectively either dark or bright in the unexcited state. This is so because in the unexcited state the liquid crystal molecules rotate the polarization of the incident light 90 degrees. The nematic LC molecules have an alignment director parallel to the cell surfaces, and its direction changes by 90 degrees in going from one cell surface to the other, hence the name *twisted nematic* (see Figure 1). Applying a voltage of the order of 5 V aligns the molecules with the electric field which is normal to the cell surface. In this orientation, the LC molecules no longer rotate the plane of polarization, and the light transmission of the cell is changed.

A typical, normally white transmission voltage (T-V) curve is shown in Figure 2 for a TN liquid crystal cell. The T-V curve depends on the viewing angle—one of the LC characteristics needing improvement—and the curve shown is for viewing normal to the display. For a fixed viewing angle, the transmission is controlled by the RMS value of the excitation, a feature we exploit. Excitation wave shape is unimportant, though its mean value must be zero to within a few millivolts to prevent electrochemical degradation of the liquid crystal cell. Light transmission is constant and high for voltages less than the threshold voltage V_T , and is approximately constant and low for voltages greater than V_{ON} . Between V_T and V_{ON} there exists a sigmoid-type transition region within which excitations to achieve gray levels occur. Typical values are $V_T = 1.5 V_{RMS}$ and $V_{ON} = 4.5 V_{RMS}$.

Figure 2 also shows that nonuniformly spaced excitation voltages must be used to produce uniformly spaced luminance levels, should that be desired. More generally, the nonlinear transformation from voltage to luminance complicates the design of the data drivers and requires a

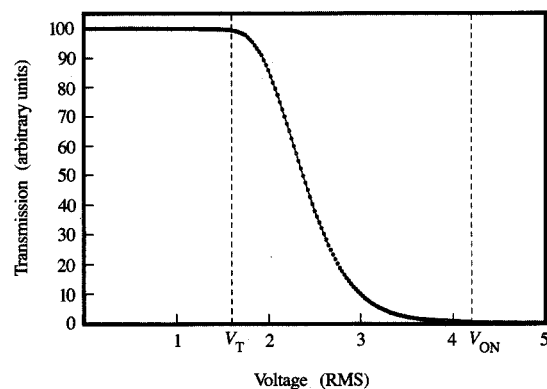


Figure 2

Typical transmission-voltage curve for a first minimum TN LC cell. This calculated curve has been normalized to the maximum transmission of the cell, which was 36%. This normally white characteristic can be converted to normally dark by aligning the polarizers parallel instead of perpendicular to each other.

compensating function somewhere in the display subsystem. The shape of the T-V curve is sensitive to many LC cell design parameters and will change as LC cell design advances. The compensating function, however it is implemented, must therefore admit to inexpensive changes. It is, for example, impractical to have this function cast in silicon in the data drivers.

TFT array A simplified electrical schematic of a TFT/LC display is shown in Figure 3. The LC cell is modeled as a capacitor with low leakage. When there is a coincidence of gate and data signals, the LC charges to the voltage on the data line. When the gate signal terminates, the TFT is left in a high-impedance state, electrically isolating the charged LC cell from subsequent signals on the data line. However, the LC charge, which controls the cell transmission, leaks away. It discharges through R_{LC} and to a much smaller extent through the TFT OFF impedance. A transmission state is maintained by periodically refreshing the LC cell once each frame time; each gate line is excited in sequence—progressive scanning—and the sequence is repeated at the frame rate. The frame frequency is typically 60 Hz or higher to minimize flicker. The time allotted for charging a LC cell is the frame time divided by the number of gate lines. Thus, the electrical performance of the TFT array must increase as display resolution increases and/or frame frequencies increase. Otherwise, the LC cell will not charge fully in the available time. This



is an issue because the amorphous Si TFTs have low mobilities and the gate lines are dissipative delay lines.

Driver circuits Driver circuit design is strongly influenced by factors other than the specific function required. The sheer number of drivers limits the complexity any one driver can have. A VGA-resolution TFT/LC display requires $(640 \times 3) + 480 = 2400$ data + gate drivers. At, say, 240 drivers per chip, a display needs 10 chips, a reasonable display system design point but an aggressive driver chip goal. These chips must be small to

The gate drivers do not present a large problem. Relatively few gate drivers are needed, their outputs are bilevel, their clock rates are less than 100 kHz, and the function required is simple—a shift register with line drivers. Though the operating voltage may be as high as 25–30 V, consumer-grade digital CMOS circuitry works well and is inexpensive. Circuitry used for years to drive simple matrix LC displays has also been used as gate line drivers for TFT/LC displays.

What evolved instead of all-analog drivers were digital-input CMOS data drivers [2]. This was a natural early development, since the first TFT/LC displays were designed to be bilevel. Such displays had less demanding uniformity requirements and good viewing angles, and the existing digital-input, bilevel drivers for simple-matrix LC displays could be used. TFT/LC technology progressed more rapidly than the circuitry, however, and displays capable of color and gray scale appeared, but were burdened with bilevel drivers. Subsequent developments in TFT/LC data drivers provided multilevel outputs, but with digital inputs [3]. This has resulted in the often-noted comment that the natural interface to TFT/LC displays is digital, though this comment is at best imprecise.

Implementing gray scale in TFT/LC displays

The most direct way to implement gray scale in an LC display is to attach analog drivers to the data lines of the panel. Such drivers, having either digital or analog inputs, will generate a voltage level on the LC cell related to the desired pixel intensity. As already mentioned, such drivers were initially unavailable for VGA performance displays; even today, the standard is a three-bit driver which

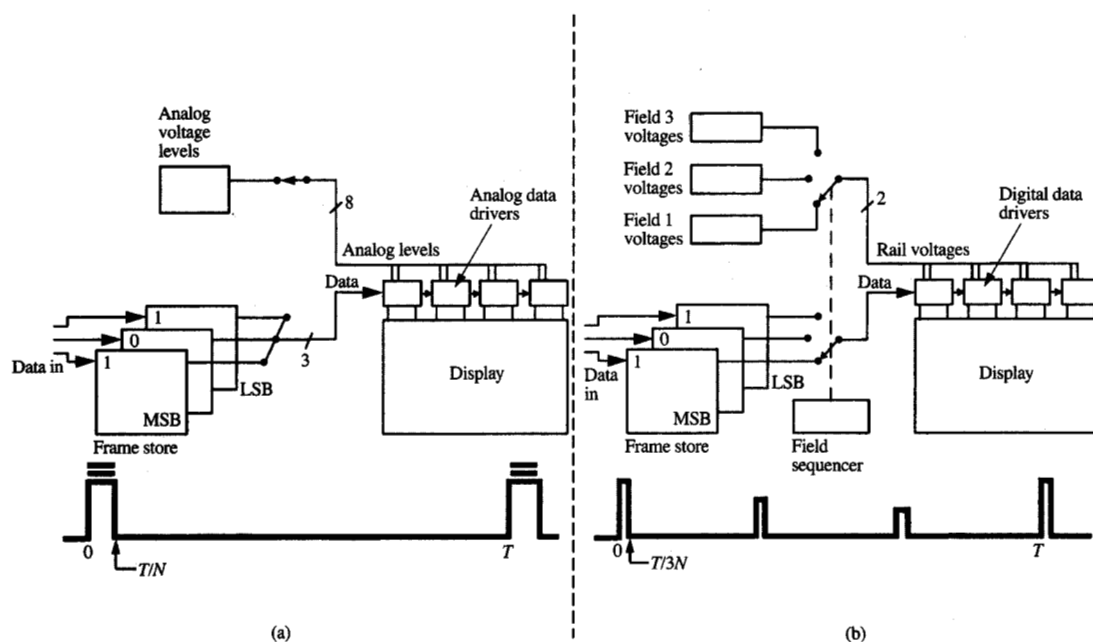


Figure 4

Simplified diagram of two implementations of gray-scale addressing. In (a) the standard (analog) implementation is shown. Three-bit data are decoded in the driver to select one of the eight levels bussed to all data driver chips. In (b) we show the implementation discussed in this paper. Inexpensive digital drivers are used in this case.

operates by selecting one of eight discrete voltages to excite the LC. A simplified diagram of how that system operates is shown in **Figure 4(a)**. The waveform at the bottom of the diagram suggests that a signal with one of several discrete amplitudes and pulse width T/N is applied to an LC pixel repetitively [T is the frame time and N is the number of horizontal (gate) lines in the display]. A VGA display has a T/N value of $\sim 30 \mu\text{s}$. Lacking drivers with sufficient amplitude resolution, the question is whether one can operate the display in some other way to achieve gray-scale operation. Various combinations of pulse amplitude, pulse width, and frame-time modulation are possible. Each has some performance cost associated with it; a detailed comparison is beyond the scope of this paper, though some brief descriptions follow.

In principle, one can use pulse-width modulation to control the charge which the TFT places on the LC cell. The tight uniformity requirements on TFT characteristics and the relatively slow dynamics of both the amorphous silicon TFTs and the gate-addressing lines make this approach unattractive. Another approach described in the literature produces gray-scale images on ac gas discharge displays which are inherently binary in operation [4, 5].

This technique uses multiple subfields per frame. The field times are in a binary sequence, and the perceived intensity of a pixel is proportional to the sum of the times that the subfields of the pixel were turned ON. This technique requires fast optical response of the display and a row-line addressing scheme which is not a linear sequence. TFT/LC displays have a slow response and cannot use this scheme directly. In addition, existing row drivers do not have the line-addressing capability required of this scheme, though it could be designed into new chips. Simple matrix STN (super-twisted nematic) LC displays have bilevel drivers but are made to display different luminances by a technique called *frame rate control* (FRC). A strictly periodic sequence of addressing pulses produces the full ON level. By eliminating some of the excitation pulses, for example using only five out of seven pulses, the time-averaged LC excitation is reduced and the luminance is changed. This approach increases the luminance signal modulation and lowers the fundamental frequency components it contains. Both effects contribute to make flicker a serious problem. This is partially suppressed by controlling the relative phasing of excitations to neighboring pixels having the same luminance. This shifts

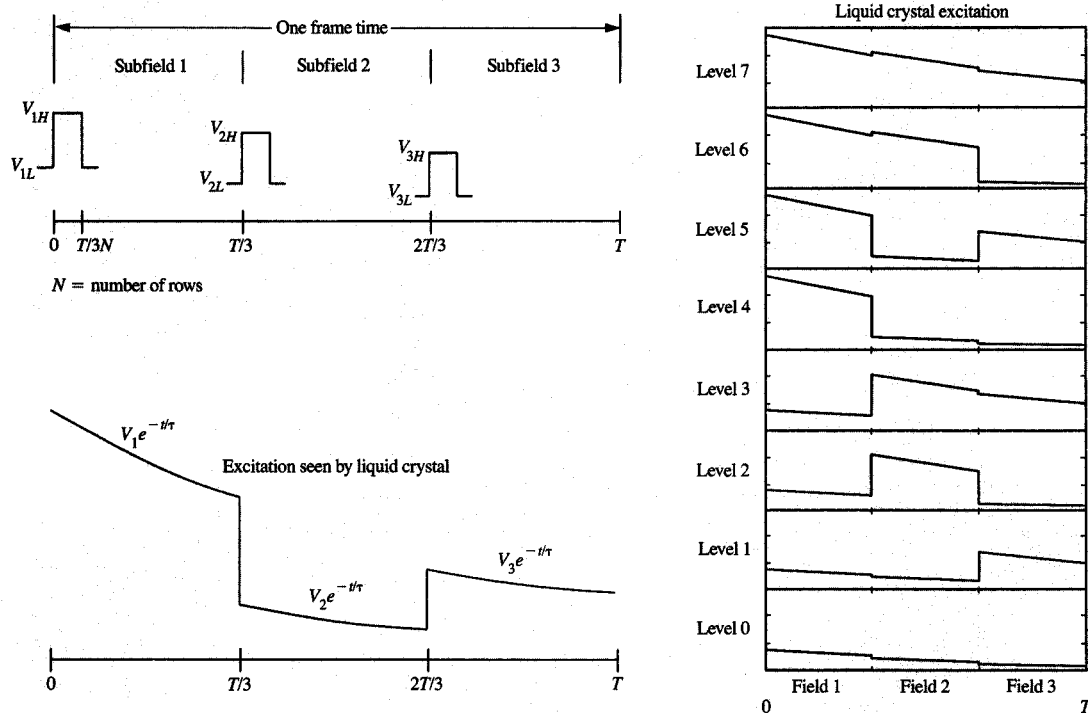


Figure 5

Diagram showing the voltage levels and timing relationships of the gray-scale technique using digital drivers. The voltage decay of the LC cell is exaggerated. On the right the eight combinations of excitations seen by the LC are shown vs. time. The opposite polarity waveforms to achieve zero net dc excitation are omitted from the drawing.

the flicker components to high spatial frequencies where viewers perceive flicker less. TFT/LC displays have much faster LC response times than do STN displays, and the flicker problems are correspondingly worse using FRC.

- *A new technique*

The technique described herein uses conventional row addressing (linear sequence), bilevel (digital) drivers, and multiple, equal-duration subfields per frame. The number of subfields controls the number of gray levels. The technique relies on the LC cell averaging the dynamic excitation to produce an effective (RMS) excitation. In effect, the LC cell becomes a digital-to-analog converter. If this were the extent of the technique, one would have a limited scheme. By using three subfields and binary excitation, for example, a pixel may be excited, or not, three times each frame. While that presents eight combinations, only three ON combinations are unique, since the excitation voltage and duration in each field are the same. These ON states and the OFF condition give just four gray levels. In addition, the spacing in luminance

between ON levels is not controllable. To solve these limitations, the following modifications based on the characteristics of the existing digital data drivers are made. At the end of each subfield, the bus voltages feeding the drivers are changed to new levels. While the drivers are referred to as digital and are used to drive displays in a binary fashion (ON and OFF states only), they are, in fact, versatile drivers whose output levels are set by external voltages having any value within a wide operating range; all drivers in a package, however, switch between the same two bus voltages, so there is no way to have adjacent drivers, for example, at different voltages.

The high and low levels, between which the drivers switch, can be changed each subfield. With multiple subfields, this approach provides digital, field-amplitude-weighted, frame-time-averaged modulation. We use the shorthand phrase *digital gray scale* for this technique. A pictorial description of the timing of the data pulses and the excitation seen by the LC is given in Figure 5, and a system-level diagram is shown in Figure 4(b). In general terms, the relationship between the gray-scale liquid

crystal voltages, V_{gs} , in each field and the levels between which the drivers switch can be described by a set of equations. Consider an example in which we choose three subfields. Using the voltage subscript notation defined in Figure 5, the following equations obtain:

$$\hat{V}_{1L} + \hat{V}_{2L} + \hat{V}_{3L} = V_{gs0}^2 = V_{OFF}^2, \quad (1)$$

$$\hat{V}_{1L} + \hat{V}_{2L} + \hat{V}_{3H} = V_{gs1}^2, \quad (2)$$

$$\hat{V}_{1L} + \hat{V}_{2H} + \hat{V}_{3L} = V_{gs2}^2, \quad (3)$$

$$\hat{V}_{1L} + \hat{V}_{2H} + \hat{V}_{3H} = V_{gs3}^2, \quad (4)$$

$$\hat{V}_{1H} + \hat{V}_{2L} + \hat{V}_{3L} = V_{gs4}^2, \quad (5)$$

$$\hat{V}_{1H} + \hat{V}_{2L} + \hat{V}_{3H} = V_{gs5}^2, \quad (6)$$

$$\hat{V}_{1H} + \hat{V}_{2H} + \hat{V}_{3L} = V_{gs6}^2, \quad (7)$$

$$\hat{V}_{1H} + \hat{V}_{2H} + \hat{V}_{3H} = V_{gs7}^2 = V_{ON}^2. \quad (8)$$

In these equations the hat symbol signifies the mean square voltage on the liquid crystal produced by applying a peak voltage of the same subscript. The relationship between peak and mean square voltage follows:

$$V_{eff}^2 = \frac{1}{T} \int_0^T V^2(t) dt, \quad (9)$$

$$V_{eff}^2 = \frac{1}{T} \left[\int_0^{\frac{T}{3}} V_1^2(t) dt + \int_{\frac{T}{3}}^{\frac{2T}{3}} V_2^2(t) dt + \int_{\frac{2T}{3}}^T V_3^2(t) dt \right], \quad (10)$$

$$V_{eff}^2 = \hat{V}_1 + \hat{V}_2 + \hat{V}_3, \quad (11)$$

$$\hat{V}_i = V_{ip}^2 \tau / 2T (1 - e^{-2T/3\tau}). \quad (12)$$

In these equations, T is the frame time, τ is the decay time constant of the LC voltage, and V_{ip} is the peak voltage (the digital level). The effective voltage, for a fixed peak voltage, depends on τ . If τ is much larger than T , the dependence is small. With use of the latest materials and processing techniques, the LC charge may decay only a few percent in a frame time. In some displays used in this study, however, charge decay as large as 40 percent was measured. Moreover, τ may vary considerably over the panel, producing nonuniform excitation for the same peak voltage. This condition is of no greater consequence for this addressing scheme than it is for a display with multilevel or true analog drivers. In all cases the TFT switch samples the data voltage, turns off, and then depends on low leakage to maintain charge (electric field excitation) on the liquid crystal. To the extent that leakage varies with pixel position (or temperature), one loses the ability to provide uniform display luminance.

In this example, eight distinct excitations are applied to the LC, producing eight gray levels. Idealized waveforms of the excitations are shown on the right side of Figure 5. The important characteristic of each waveform is its RMS

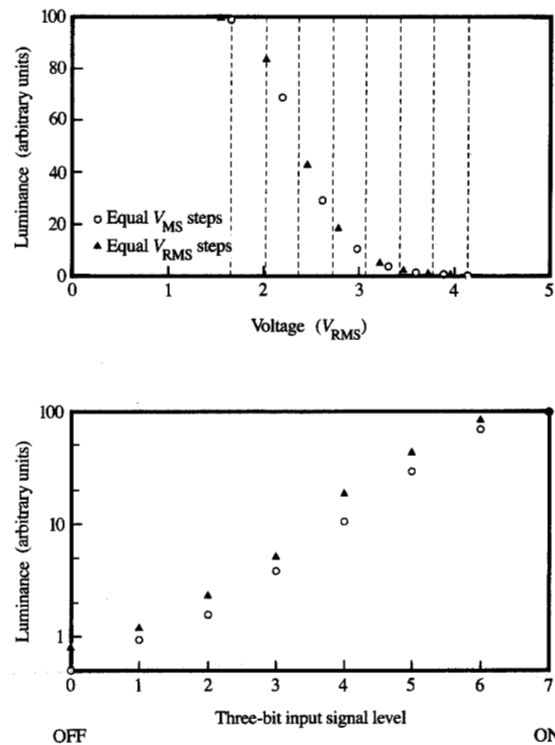


Figure 6

The upper data set shows with circles the pixel luminance available when uniform steps in mean-squared voltage are produced by the multifield addressing technique. Triangles show the cell transmissions when we do a best approximation to equal RMS voltage steps. The vertical lines are the target voltages of the 3-bit addressing scheme. The lower drawing shows the same data plotted as a function of the 3-bit signal levels.

value. The technique also applies to any number of fields per frame. There are 2^F gray levels, where F is the number of fields per frame. The excitations must have zero dc content, though for clarity of presentation all the drawings show only one polarity. Zero dc content is easy to implement.

The system described by Equations (1)–(8) is overconstrained, having eight equations and six unknowns. Thus, while one can generate eight luminance levels, they may not be the desired levels. It is worth looking at some of the constraints imposed by this driving scheme. The one condition we can fulfill exactly is to have equal steps in mean-squared LC voltage, V_{gs}^2 . These steps can be positioned anywhere within the transition region of the T-V curve, for example. Calculated luminance values for equally spaced mean-squared voltages are plotted with circles in Figure 6. The T-V curve of Figure 2 was used,

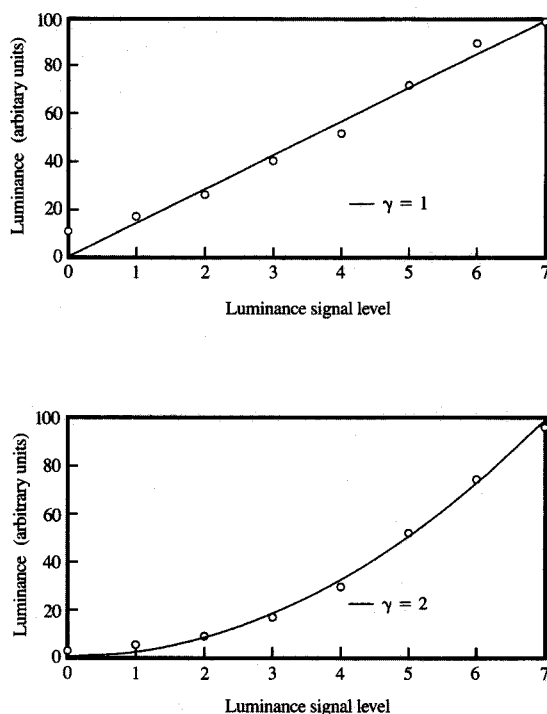


Figure 7

Digital gray-scale approach in tuning the display response to often-used γ functions. These data were calculated using three subfields, $T = 0.016$ s, and $\tau = 0.300$ s.

and the transition region was taken to extend from $T = 99\%$ to $T = 0.5\%$, a rather large span. The lower figure shows the same data plotted logarithmically against the 3-bit signal level or gray level. For comparison the figure also shows the resulting luminance if one attempts to produce equal steps in LC root-mean-squared voltage. In this case, however, since the equations cannot match the eight points of the 3-bit code exactly, a numerical procedure was used to minimize the vector difference between the target and the resulting LC voltages.

The comparison relevant to rendering images is how close the luminance levels are to some specified luminance-signal function. Two cases, luminance L proportional to signal level S and luminance proportional to the square of the signal level, are considered. These are two special cases of the general behavior $L = S^\gamma$. The condition $\gamma = 1$ is desirable for display-independent renderings, and $\gamma = 2$ approximates the behavior of a CRT display attached to a PS/2 system. If the same rendering is desired simultaneously on CRT and LC displays, the LC display should exhibit a γ of 2. In these cases, the

minimization technique must include the nonlinear T-V curve. The procedure is to pick the six voltage levels, V_{ip} in Equation (12), such that the resulting eight-component luminance vector, derived from Equations (1)–(8) and the T-V curve, is as close to the desired luminance vector as possible. The results of these calculations are shown in **Figure 7** plotted as circles. The same maximum and minimum luminance values were chosen as in the above examples. In both cases the fit is poorest in the dim regions, though a difficult target value of 0.5% was chosen. The important $\gamma = 2$ case is seen to be practical for this addressing scheme, and the signal levels also present no engineering challenge, having the following values:

$$V_{1L} = 1.95, V_{1H} = 4.25, V_{2L} = 1.73, V_{2H} = 3.15,$$

$$V_{3L} = 1.77, V_{3H} = 2.65.$$

The voltage levels calculated above are not unique; that is, other voltage vectors producing the same luminance vector are allowed. Only four of the six levels are independent. One could, for example, have all the upper levels the same. There is an experimental advantage to having six instead of four voltage levels when trying to adjust the display to some desired performance. With six voltage levels, fewer luminance states are perturbed when one voltage is adjusted.

Experimental results

Since the motivation of this work was to evaluate the gray-scale image quality on TFT/LC displays, the above scheme was implemented on several full-size prototype displays. The fundamentals of the scheme are based on well-understood principles, so the only uncertainties arise from the dynamics and parasitics of the chosen displays. The above example used three subfields per frame. This means that only a third of the $\sim 30\text{-}\mu\text{s}$ line time for a 480-line VGA display is available. Measurements were taken on a 14-inch-diagonal, 1440-column $\times$ 1100-row prototype display to determine whether the gate line delay and the speed of the TFTs were sufficient to operate at high frame rates. The luminance of two vertically adjacent single pixels near one edge of the panel were measured as a function of gate pulse width. Since even-numbered gate lines are driven from one side and odd-numbered lines from the opposite side, the data represent pixel response with and without gate pulse distortion. The lines per frame were set at 482, the full panel was excited, the frame rate was 60 Hz, the field rate 180 Hz, polarity was reversed at 60 Hz, and the data ON voltage in the subfields was constant at 5 V. The data line signal contained OFF levels for rows before and after the row under test and an ON level for the test row. **Figure 8** shows the results of that measurement. These results suggest that gate pulse widths in the range of 7–10 μs are required for reasonable

operation on this large panel at high frame rates. Each TFT array design would have different results. The far-end luminance decreases for larger pulse widths because the slowly falling edge of the distorted gate pulse extends into the next gate line time when the data have changed to a low level and discharging occurs. A curious result—not important to this work—appears in Figure 8, which shows the far-end pixel turning on before the near-end pixel. This may be related to two effects: variations in the TFT characteristics and the significant difference in the parasitic C_{gs} effect because of the drastically different gate pulse fall times. The details of this effect are sensitive to the data voltage at which the measurement is taken.

We built a versatile display controller to implement the *digital gray-scale* technique. A simplified description of the system is shown in Figure 4(b). Architecturally, the most significant difference between this and conventional controllers is that while the frame buffer is written in conventional raster order at F bits per pixel, it is read at one bit per pixel for F consecutive fields. A PC supplied data to a frame buffer which could be read at a rate controlled by a variable clock. All related times except

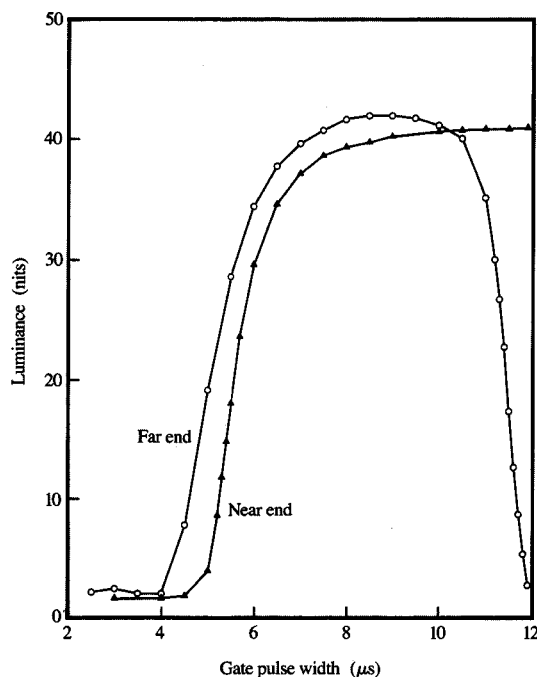


Figure 8

Time-averaged luminance vs. gate pulse width. The luminance from two single pixels, one near and one far from the driver, shows the effects of gate pulse distortion. (1 nit = 1 cd/m².)

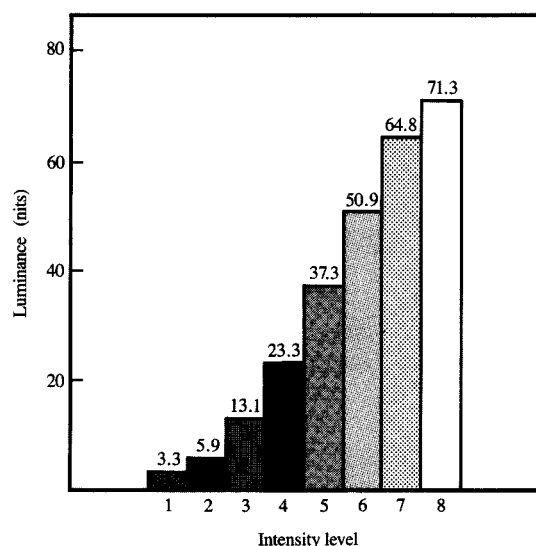
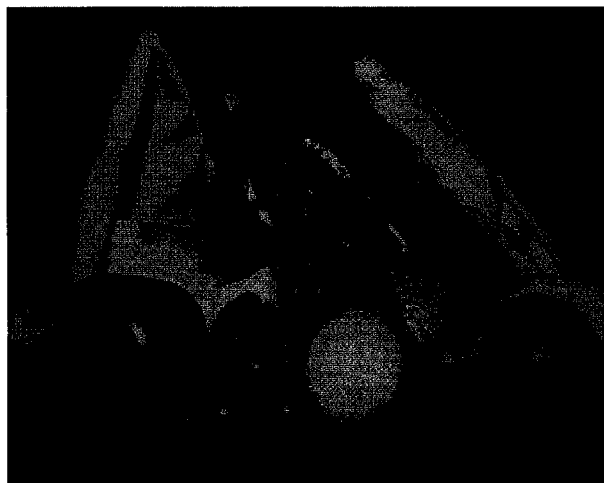


Figure 9

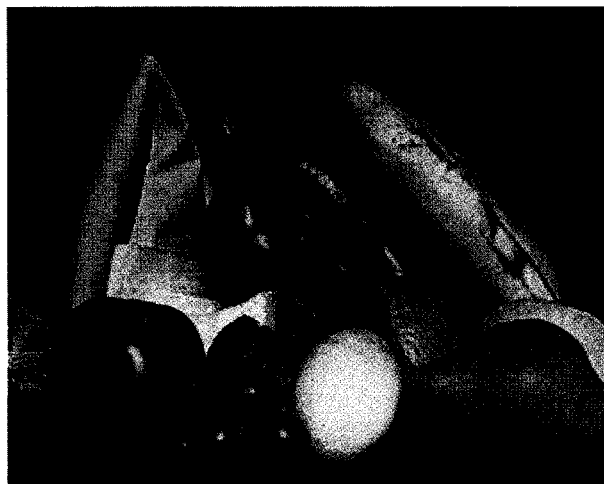
Measured γ of the TFT/LC display adjusted for best subjective appearance of the images.

gate-pulse enable times scaled with the clock; gate-pulse widths were adjustable but not clock-controlled. Progressive and interlaced scanning of the display was provided. Preliminary results using three fields per frame were very successful, so the system was built to accommodate four fields per frame. Thus, we had independent control of eight voltage levels. Provided the voltage levels were readjusted, one could select from one to four fields or, equivalently, two to 16 gray levels per color. To accommodate four fields and the optimum line-time requirements, the frame rate was reduced to about 50 Hz. Flicker was not a problem, presumably because the voltage modulation field-to-field is small compared to conventional excitations. Color and monochrome panels were tested.

In experiments where the most pleasing rendering of images was the goal, we used a two-step technique. First, the various field voltages were adjusted so that a 16-step luminance scale was approximately correct to the eye. Then, several images containing smoothly varying tones, including human faces and computer-generated spheres, were displayed and the voltages readjusted to give subjectively evaluated good renderings. The measured luminance-signal characteristic set this way for the panel mentioned above is given in Figure 9. Examples of the renderings are shown in Figures 10 and 11. Figure 10



(a)



(b)

Figure 10

Close-up photographs of one quadrant of a 14-inch-diagonal, quad-pixel color display. The top photo shows an image rendered by simple thresholding. The display has bilevel drivers. The lower photo shows the same image rendered on the same display using the four-field digital gray-scale approach allowing 16 levels of gray.

contains a close-up photograph of one quadrant of a 14-inch-diagonal display containing 720 by 550 quad pixels. A quad pixel consists of red, green, blue, and white subpixels of identical square size. A comparison is shown between bilevel and 16-level renderings. In these renderings, an additional bit of information is included. The white pixel of each quad is supplied with the luminance equivalent of the remaining three pixels; that is, the white pixel signal is $0.59 \times G + 0.30 \times R + 0.11 \times B$, where R , G , and B are the intensities of the red, green, and blue pixels. The resulting image is not chromatically

correct, but the subjective difference is slight, the image is brighter, and it is the rendering preferred by viewers in comparison to using only R , G , and B pixels—viewers prefer bright displays.

Discussion

The digital gray-scale scheme was devised to overcome a temporary problem. We needed to evaluate our display technology for rendering contone color images, but the displays had bilevel drivers which severely limited the types of evaluations which could be done. The drivers were rather flexible, however, and taking advantage of their characteristics allowed us to proceed with the gray-scale studies. An evaluation of the addressing scheme itself is worthwhile.

Our experiments have shown that amplitude-weighted, multifield excitation with bilevel drivers is equivalent to conventional single-field excitation with analog drivers. This is not surprising, since LC response to time-varying excitations has been understood for a long time. What is a little surprising is that all the elements needed to work in a complete system merge as well as they do. The dynamics of the TFT and LC, the RC transmission line we call the gate bus, and the operation of the controller and image buffer all have characteristics that allow digital gray-scale operation on conventional displays.

Interest in multifield excitation has grown because progress in analog TFT/LC drivers has been slow and the added costs for amplitude resolution high. Independent work on CdSe drivers [6] has also suggested changing the power supply voltage in frame synchronism to achieve gray scale, though no implementation has been presented. The most interesting comparison is with frame rate control, as mentioned earlier. This technique, implemented in controllers for STN LC displays, was developed for similar reasons: The displays were available only with bilevel drivers, and many computer applications required gray scale. In frame rate control the data voltage is constant, and one or more refresh pulses are stolen from a pixel to produce intermediate tones. This reduces the LC RMS voltage and changes the transmission. However, to produce 16 different levels one may need a repeat period of nine or more fields, depending on the extent to which one wishes to control the transmission levels. This allows duty cycles of, say, $1/2$, $1/3$, $2/3$, $1/4$, $\dots$, $1/9$, but flicker at the low transmission levels (submultiples of the basic frame rate) is a severe problem. However, sixteen gray levels can be achieved with just four fields if one modulates the data voltage on a field basis. Furthermore, since the voltage modulation between frames is small compared to the full ON or OFF excitations of FRC, the corresponding flicker is less.

The price one pays for multifield schemes, assuming that the lowest-frequency components are fixed by flicker

requirements, is high bandwidth and, consequently, higher power. Every component in the system runs at F times single-field rate, where F is the number of fields. However, that is the direction in which display technology is headed with faster TFTs, better gate metallurgy, and faster memory and processors.

The obvious extension of the digital gray-scale approach is to display systems with drivers having more than two voltage levels but fewer than the number needed. With only two subfields and three bit drivers, the number of available gray levels can be doubled from eight to 16. This increases the number of colors available from 512 to 4096. Work of this type has already been published [7] and is likely to continue until economical, high-performance analog drivers are developed.

Acknowledgments

The authors wish to acknowledge the excellent work of the TFT/LC development team at the IBM Yamato Laboratory. Most of the prototype panels used in this study were created by this group. We also thank K. H. Yang for providing T-V data, Peter Zug for helping with the minimization problem, and R. Feigenblatt for significant image generation and software support.

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Received August 21, 1991; accepted for publication December 18, 1991



Figure 11

Photograph of a 12-inch-diagonal display having 720 by 480 quad pixels. Sixteen levels of gray are rendered.

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