36.1: Display Modeling and an AMLCD Model on a Video Supercomputer

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Abstract: An active-matrix liquid crystal display (AMLCD) is simulated on a cathode ray tube display driven by a video supercomputer, the Princeton Engine. The supercomputer permits the use of real-time video in conducting human factors visualization tests. The display model produces a representation that visually matches an actual AMLCD display for a wide range of viewing angles.

INTRODUCTION

Determining the quality of an image produced by a pixelated display requires at least an understanding of the photometric behavior of the display and the sensitivity of the human vision system to the display behavior. The former can be accomplished by relevant colorimetric measurements using static and dynamic test patterns, while the latter requires simulating a continuous range of display behavior and correlating this to human vision sensitivity using subjective tests. Simulating display behavior requires that a model of the display be developed.

Modeling of displays composed of discrete pixels typically have their focus on helping manufacturers produce better displays and proving design concepts prior to the construction of manufacturing prototypes. Advanced display models may be rather complex by including models of the display driver electronics, the electro-optical transducer, color filters or phosphors, and the pixel configuration on the display. Using such models to produce a simulated display image may require several hours of computation per image [1-8].

For practical subjective tests the display simulation system must respond nearly instantaneously to user changes in model parameters. This requires either pre-computing all possible display conditions on all images and storing them for fast recall, or using a simplified model that produces images that are visually identical to the display image. The simulation presented here models the relevant visual aspects of an active matrix liquid crystal display (AMLCD) and produces the simulated video images on a cathode ray tube (CRT). We run our display simulation on a video supercomputer which accepts continuous video input and processes the input video in real time according to the display model. The simulation is under direct control of the test subject, who may adjust the model parameters and view the changes immediately [9,10].

Real-time video processing offers two advantages over static imagery: 1) a large variety of video source material can be examined quickly (30 frames per second), and 2) test subjects may interact with the simulation to produce a more accurate quantization of image defects. Typical subjective test procedures involve a test subject comparing a reference image to an impaired image to determine if the difference is detectable. With real-time simulation the test subjects may adjust the model parameter of interest as they observe when the effect becomes visible (or invisible).

VIDEO SUPERCOMPUTER

The NIST Princeton Engine† is a massively-parallel video supercomputer designed for the capture, processing, and display of video images in real time [11]. During operation, incoming video is digitized and clocked into a shift register; at the conclusion of each scan line, the data are transferred to a linear array of 1024 processors. Processing proceeds, according to a stored program, during acquisition of the next video scan line while the processed data from the previous scan line are displayed on a color monitor. Since processing occurs simultaneously with acquisition and display, infinitely long video sequences can be processed and viewed.

Selected parameters within the stored program may be adjusted during run time for immediate viewing of the effect. With the simulation described here the operator may change such characteristics as the apparent panel pitch and yaw angles, video brightness, contrast, saturation, tint, and the color transformation matrix elements.

AMLCD EMPIRICAL MODEL

Our goal is to simulate the viewing angle artifacts of an AMLCD on a CRT. To accomplish this, empirical viewing-angle data are obtained from a commercial AMLCD used for video display, and these results are incorporated in a program running on the Princeton Engine. The angles and coordinates relative to the flat panel display (FPD) surface are

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† *The identification of any commercial items in this paper is made in order to specify the experimental procedure. Such identification does not imply endorsement by NIST, nor does it imply that the items identified are necessarily the best for the purpose.*

specified in Fig. 1 with ϕ as the azimuthal angle or yaw and θ as the pitch angle, both measured from the normal (z axis). In our notation T is a three-component column vector of the tristimulus values $T = (X,Y,Z)$. The color T depends upon the viewing direction (θ,ϕ) as well as the red-green-blue (RGB) stimulus from the video signal at the pixel position. The data collected to describe T are taken with the RGB stimuli equal, i.e., only gray levels are used. Thus, in Fig. 1, T is expressed also as a function of u which is the IRE (International Radio Engineers) video signal value where u = 0 IRE is sub-black, u = 7.5 IRE is black, and u = 100 IRE is white for an NTSC (National Television System Committee) composite signal.

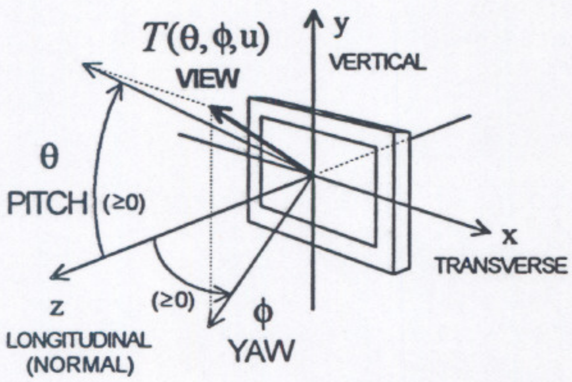

Fig. 1. Coordinate system for FPD measurements.

We use the following notation: serif italic fonts represent either the tristimulus column vectors $T = (X,Y,Z)$ or the RGB component column vectors $E = (R,G,B)$; sans serif fonts A represent 3x3 matrices; boldface serif fonts **G** are functional operators which do not mix the components but operate identically on each component separately; and a boldface sans serif font **H** (used to denote the Princeton Engine signal processing) is any combination of functional operators and matrices.

In an NTSC television CRT receiver, the transmitted composite signal is decoded into its component RGB signals and passed to the CRT. At the source of the transmission the RGB signals were nonlinearized by an opto-electronic transfer function $\mathbf{G}_C^{-1}$ in anticipation of an electro-optical transfer function $\mathbf{G}_C$ at the receiver in the form of the nonlinear characteristics of the electron guns in the CRT. According to the SMPTE 170M standard, in our notation these functional operators are [12]:

$$\mathbf{G}_C^{-1} E_i = \begin{cases} (1+a)E_i^{1/\gamma} - a, & \text{for } c \le E_i \le 1 \\ (10/\gamma) E_i, & \text{for } 0 \le E_i < c, \end{cases} \qquad (1)$$

and

$$\mathbf{G}_C E_i = \begin{cases} [(E_i + a)/(1+a)]^{\gamma}, & \text{for } d \le E_i \le 1 \\ (\gamma/10) E_i, & \text{for } 0 \le E_i < d, \end{cases} \qquad (2)$$

where $a = 0.099$, $\gamma = 2.2222... = (1/0.4500)$, $c = 0.018$, $d = 0.0812$, and E_i represent the RGB components.

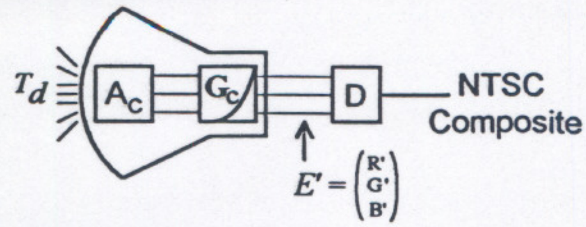

Fig. 2. NTSC television CRT receiver.

The basic CRT model used here is shown in Fig. 2. A video signal is decoded at the receiver and separated into RGB component signals. We will use a prime to denote a "gamma" corrected component signal $E'_i = \mathbf{G}_C^{-1} E_i$. The electron guns apply an electro-optic operation $\mathbf{G}_C$ to the component (R',G',B') signal whereby the component electron beams (R,G,B) are then converted to the display color T_d at the phosphor surface according to the color matrix A_C which depends upon the colors of the phosphors and the chosen white point. This signal-to-light conversion may be written as

$$T_d = \mathsf{A}_C\, \mathbf{G}_C\, E', \qquad (3)$$

where we have started with the "gamma" corrected component signal after the decoder.

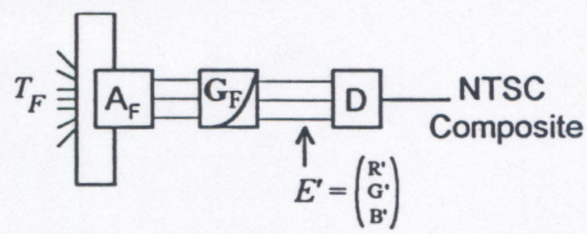

Fig. 3. NTSC television FPD receiver for AMLCD model.

The AMLCD model is shown in Fig. 3. The assumptions implicit in this model are at least twofold: 1) the decoder is identical to the CRT decoder so that the E' signals are the same for both models, and 2) there is no display matrix employed between the decoder and the nonlinear component operator. This second assumption is employed in both the CRT model and this AMLCD model. Strictly speaking, these are not necessarily correct, but in view of the overall success of the AMLCD model described here, they are adequate approximations. This model produces an output color T_F by first applying an electro-optical operator $\mathbf{G}_F$ to the "gamma" corrected component signals E', then transforming the RGB signals via the color matrix A_F we obtain

$$T_F = \mathsf{A}_F\, \mathbf{G}_F\, E'. \qquad (4)$$

The color matrix A_F is obtained from the color filters, the backlight used, and the resulting white point. The operator $\mathbf{G}_F$ embodies the nonlinear electro-optical properties of the AMLCD pixel, any nonlinearities incorporated into the activating circuits, and the viewing angle dependence of the AMLCD. In this paper, $\mathbf{G}_F$ is measured empirically.

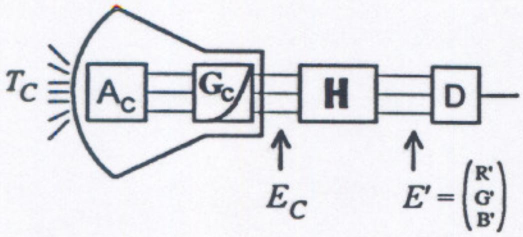

Fig. 4. Video supercomputer AMLCD model on CRT.

Figure 4 shows the arrangement to model an AMLCD with a CRT. The video supercomputer supplies the generalized conversion **H** to accomplish the modeling. The stipulation that the CRT look like the AMLCD amounts to requiring that the color produced by the CRT be the same as the color displayed on the AMLCD, or

$$T_C = A_C\, G_C\, E_C = T_F\,. \qquad (5)$$

The requisite signal injected into the CRT is E_C, and by using Eqs. (3)-(5) it is found to be

$$E_C = \mathbf{H}\, E' = (G_C^{-1} A_C^{-1} A_F\, G_F)\, E'\,, \qquad (6)$$

which defines the required generalized transformation **H**. The sequence of operations in the Princeton Engine program is dictated by the order of operations in the parentheses. First the angular-dependent, electro-optical operator modifies the decoded signal; then the color matrix for the FPD adjusts the color; next the effects of the CRT color matrix are canceled; and, finally, the effects of the CRT's nonlinearity are canceled. When this signal E_C is fed into a CRT, as in Eq. (3), the net result is the color T_F described in Eq. (4).

MEASUREMENTS

The color matrices A_C and A_F are obtained straightforwardly. For the CRT we employ the SMPTE [10] phosphor chromaticity coordinates and a D_{65} white point to calculate the color matrix. For the AMLCD we measure the chromaticity coordinates (x,y) on the 1931 CIE (Commission Internationale de l'Eclairage) diagram of the saturated RGB colors and of the white screen: Color (x,y) = Red (0.589, 0.319), Green (0.297, 0.623), Blue (0.144, 0.077), and White (0.281, 0.303) having a combined standard uncertainty of ±0.006 for both x and y based on a root-sum-square average (RSS) of the instrument uncertainty of ±0.002 and a standard deviation of the measurements of ±0.005. It is recognized that both for the CRT and the AMLCD that the color chromaticity coordinates are not independent of the pixel intensity, but for the purposes of our approximate model such irregularities are not included.

We have observed screen loading difficulties associated with the most suitable determination of G_F for all the angles needed. The luminance of a pixel depends upon the number of pixels which are activated. In Fig. 5 we show three types of screens used to determine the luminance as a function of the driving signal u. The most suitable result is obtained with the screen which provides a combination of signals in one screen. The pattern chosen provided an overall luminance somewhat comparable to a bright video picture. Only a gray-scale luminance is used to characterize the viewing angle dependence.

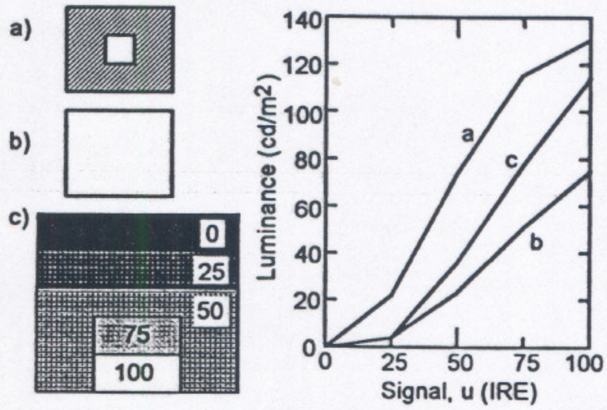

Fig. 5. Screen loading effects on luminance: a) 16% of the screen is used, b) 100% used, c) partitioned screen.

Figure 6 shows a plot of the luminance as a function of viewing angles for two of the five signal levels used: u = 0 and u = 100 IRE are displayed whereas data for u = 25, 50, 75 IRE are also obtained. These data are taken for yaw angles ϕ = 0°, 32°, 64° and for pitch angles θ = -64°, -32°, 0°, 32°, 64° with respect to the normal of the screen's surface. All angles and signal values between these data points are obtained via a linear interpolation. These measurements are made by a spectroradiometer with a combined standard uncertainty of 3% of the luminance readings (RSS average of the instrument uncertainty of 2% and a standard deviation of 1.6%). The angle of the AMLCD relative to the observation axis and the part of the screen under observation are controlled by a five-axis positioning system. The spectroradiometer's viewing aperture subtends 0.125°, and the AMLCD is placed approximately 2.6 m from the spectroradiometer.

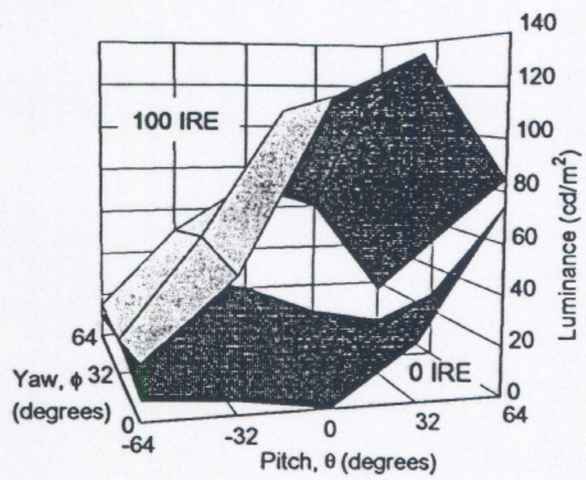

Fig. 6. Luminance vs viewing angles for two signal levels.

RESULTS

It is not practical to attempt to show the results on paper in black and white. Suffice it to say that the simulation produced on the CRT by means of the Princeton Engine visually compares well with the video displayed on the AMLCD for all viewing angles. For example, the simulation becomes bright and washed out for views from above, dark shadow areas become medium grays for low views especially from the side, and flesh tones are rendered with a spectrum of colors from reddish light flesh to blues and magentas depending upon brightness. However, the color shifts due to nonlinear processing of the non-gray RGB signals can be inaccurate. In Fig. 7 we show how flesh tones (x,y) = (0.406, 0.373) for five different intensities from dark to light are rendered at one particular viewing angle on the AMLCD compared with the Princeton Engine model. There are several reasons for these discrepancies. The "gammas" or

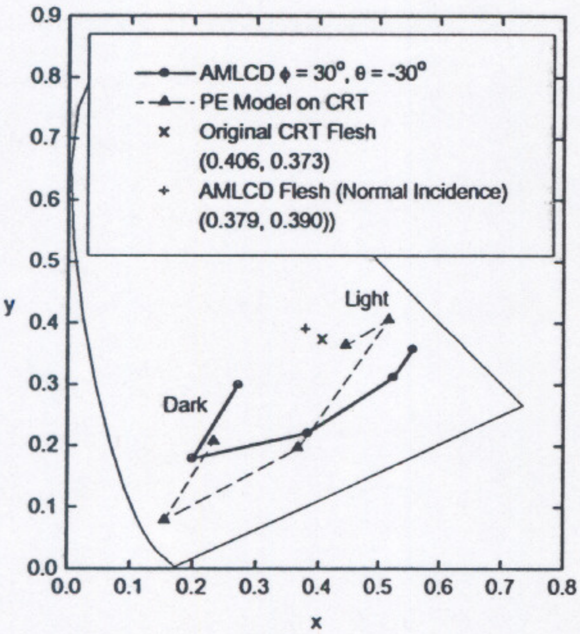

Fig. 7. Chromaticity diagram of distorted flesh tones.

nonlinear, angular-dependent, electro-optical transfer functions of the AMLCD differ depending upon which RGB color is selected; thus, using only gray levels is not adequate for rigorous accuracy. Further, screen loading depends not only on luminance but also upon color. To improve the model we would need to provide a number of angular-dependent "gammas" which span the range of screen loading conditions.

The reason the present model appears adequate is that the luminance levels are generally correct and the eye finds false colors objectionable, as with a blue- and magenta-ringed face, regardless of how accurately the blues or magentas are rendered. The model is therefore adequate for human-factors analysis of the objectionable features of viewing angle artifacts on an AMLCD while viewing real-time video without the geometric distortions associated with viewing the AMLCD.

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