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Time-dependent color simulation of active-matrix liquid crystal display adopting the field sequential driving method☆

Minkoo Kim, Dong-Gun Lee, Jeong-Sik Kim, Byung-Chang Yu, Seung-Woo Lee*

Department of Information Display and Advanced Display Research Center, Kyung Hee University, 26 Kyungheedae-ro, Dongdaemoon-gu, Seoul 02447, Republic of Korea

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ABSTRACT

A time-dependent display color simulation method is proposed. For the time-dependent simulation, we applied our behavioral model of liquid crystals (LC). The model provides the transient response characteristics of the LC. The color simulation of a twisted nematic active matrix liquid crystal display (AMLCD) adopting a field sequential (FS) driving method is possible when combining the transient LC responses with periodically operating red-greenblue (RGB) light emitting diodes (LEDs). By modifying the gate start pulse of the conventional AMLCD, we created a virtual AMLCD driven by the FS method. The color performance of the panel was measured at five vertical positions, and the results showed that the RGB LEDs should be driven by a 70% duty parameter and a 50% shifting parameter to minimize line-to-line color characteristic deviations in the AMLCD panel. By using the proposed simulation method, it is possible to find the optimal FS driving condition for any display with arbitrary response characteristics to exhibit the best color performance.

1. Introduction

Recently, the importance of augmented reality (AR) and virtual reality (VR) technologies has increased because the AR/VR market is expected to grow tremendously in the future. A holographic display is one of the most promising and challenging developments for the VR display market. Holographic televisions can provide the full parallax and depth information of a three-dimensional (3D) scene without any special eyewear devices [1,2]. To achieve this, a pixel size of a few microns or less is required for diffraction of light to occur sufficiently. The size constraint can be overcome only if the pixel structure is simple. Among various types of active-matrix liquid crystal displays (AMLCDs), such as the twisted nematic (TN), vertical alignment (VA), in-plane switching (IPS), and fringe field switching (FFS) modes, only the TN mode can overcome the tight size constraint because it has the simplest pixel structure. In addition, using a color filter array process is impossible due to the size limit. Thus, the time division method is adopted instead of the space division method to realize the desired color performance. Therefore, the TN mode AMLCD driven by the field sequential (FS) method is one of the most promising candidates for developing a holographic television. The simple concept of FS driving is shown in Fig. 1. In the FS driving method, the time period is divided into three fields (red, green, and blue fields). The period of each field is 1/180 s, and each field is driven sequentially ($R \rightarrow G \rightarrow B$). By displaying the red, green, and blue sub-images sequentially faster than the time resolution of the human eye, which is approximately 40 Hz, full color images can be created without color filters [3]. Each field consists of a data-writing period and a light emitting diode (LED) turning-on period. During the data-writing period, data are applied to each pixel sequentially from the first to the last lines. In general, the LED backlight is turned off during this period. After the data-writing period, red-greenblue (RGB) LEDs are turned on sequentially. Without the color filter array, light coming from the RGB LEDs passes through the liquid crystal (LC) that acts as a shutter or variable secondary light source. Only turned-on pixels transmit the light. Thus, the variable secondary light source is realized by achieving spatial coherence corresponding to the pixel opening [1].

There have been many studies concerning the color simulation of AMLCDs having a conventional structure with a color filter array [4–8]. These color simulation methods do not consider the temporal response characteristics of the LC. In addition, since the backlight of the conventional LCD is always on, there is no need to study the color simulation of the conventional LCD time-dependent characteristics. However, to simulate the color information of the FS-driven AMLCD, the time-dependent characteristics must be studied, because the color information of the FS-driven AMLCD is affected by the LC response characteristics and time-varying behavior of RGB LEDs. In addition, the research on the color characteristics of AMLCD driven by the FS method

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* Corresponding author.
E-mail address: seungwoolee@khu.ac.kr (S.-W. Lee).

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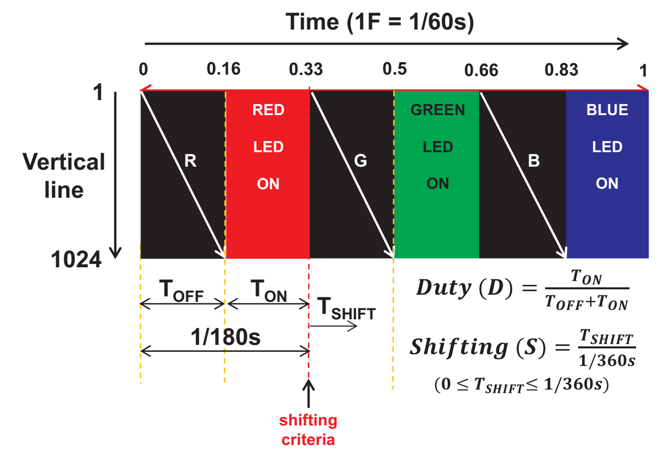

Fig. 1. Concept of the field sequential driving method.

has been focused on suppressing color breakup [9–14]. Limited attention has been paid to the fundamental color characteristics of the FS-driven AMLCD that should be addressed before the color breakup issue [15]. However, no study has discussed the color differences depending on the vertical positions of the AMLCD panel. In this paper, we propose a temporal color prediction method depending on the vertical positions of the panel for AMLCDs driven by the FS method. Considering the LC response characteristics and temporal behavior of RGB LEDs, an optimal driving condition that minimizes the deviation of the color characteristics in relation to the vertical positions of the panel is found.

2. Behavioral LC model

We proposed a behavioral circuit model to estimate the transient optical responses of AMLCDs in 2013 [16,17]. We verified the universality of the circuit model by applying it to TN, patterned VA (PVA), and IPS AMLCDs. The principle of the circuit model is based on the macro-model proposed by H. De Smet et al. [18]. In the macro-model, the motion equation is represented by Eq. (1).

$$cE^2 = Kx(t) + \gamma\frac{dx(t)}{dt} \tag{1}$$

where E, c, K, and γ are the electric field across the pixel, linear proportional constant, elastic constant, and viscosity, respectively; $x(t)$ is the average director orientation of the LC molecules with time. Eq. (1) can be written as Eq. (2).

$$V_{ext}^2 = \frac{kd^2}{c}x(t) + \frac{\gamma d^2}{c}\frac{dx(t)}{dt} \tag{2}$$

Here, V_{ext} and d are the applied voltage between two electrodes and the cell gap, respectively. We can replace the first term of the right side in Eq. (2) with v_{force}(t), as given by Eq. (3).

$$\frac{kd^2}{c}x(t) = v_{force}(t) \tag{3}$$

Finally, we can represent the equilibrium motion equation as Eq. (4).

$$V_{ext}^2 = v_{force}(t) + \frac{\gamma}{k}\frac{dv_{force}(t)}{dt} \tag{4}$$

$$V_{control}(t) = \sqrt{v_{force}(t)} \tag{5}$$

A simple resistor–capacitor (RC) circuit can represent any first-order linear differential equation, such as Eq. (4). Fig. 2 shows a schematic diagram of our circuit model. Eq. (4) can be behaviorally described using the RC circuit. To improve the accuracy, Watanabe modified the time constant (τ) concept based on Smet's approach [17]. Here, the time constant τ = RC is expressed by Eq. (6), where a_1 and a_2 are physical parameters used to represent the LC characteristics.

$$\tau = \frac{1}{a_1 + a_2 V_{ext}^2} \tag{6}$$

$V_{control}(t)$ in Eq. (5) is directly related to the LC characteristic x(t), as shown in Fig. 2. The orientation $x(t)$ of the LC molecules defines the capacitance and transmittance of the LC cell. When the information of the steady-state capacitance-voltage (C-V) characteristics of the LC is obtained for a pixel, the transient capacitance $C_{LC}(t)$ can be acquired depending on $V_{control}(t)$. However, $V_{control}(t)$ is not identical to the voltage across the LC cell. By considering the current through the pixel, the voltage of the cell can be calculated as shown in Fig. 2. Therefore, the C-V characteristics are very important in establishing the circuit model of the pixel. In addition, the transient optical responses can be obtained if the voltage-transmittance (V-T) characteristics are known. Based on Watanabe's approach [19], the behavioral model was implemented by using an analog hardware description language, Verilog-A [16].

We used a 17-in. SXGA (1280 × 1024) 60-Hz TN-mode AMLCD panel in the experiment. CA-210 with a contact-type photo probe, CA-P15, and a luminance and colorimetric analyzer were used to measure the V-T characteristics of the LCD panel with the TN mode. To extract the C-V characteristics, the optical responses were measured using a phototransistor [20]. Fig. 3 shows the optical responses of the TN-mode AMLCD panel used. The symbols and solid lines represent the experimental and simulation results, respectively. Fig. 3(a) and (b) shows the optical response of the rising transitions from gray level 0 and the falling transitions from gray level 255, respectively. This shows that the experimental and simulation results are well matched.

3. Color simulation of the FS display

Tri-stimulus values X, Y, and Z were defined by the International Commission on Illumination (CIE) in 1931, as given by Eqs. (7a), (7b), and (7c). Here, S(λ) and R(λ) can be interpreted as the backlight intensity and the transmittance of the LC, respectively, in the case of LCDs. $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the CIE's color-matching functions. Conventionally, if the tri-stimulus values of two different colors are known, the color information of a new color can be easily calculated by mixing them. To obtain the new color information, the tri-stimulus values can be added like a vector sum. If (X1, Y1, Z1) and (X2, Y2, Z2) are the tri-stimulus values of the two colors, the tri-stimulus values of the mixed color become (X1 + X2, Y1 + Y2, Z1 + Z2). Theoretically, all the color information based on an RGB subpixel structure can be easily estimated by adding the tri-stimulus values of the R, G, and B subpixels.

We proposed a new method to accurately predict color information in 2013 [21]. All colors can be expressed by mixing the RGB subpixels, but the measured tri-stimulus values of any color are not the same as the sum of the measured tri-stimulus values of each subpixel. We found that the error is caused by light leakage from the subpixels. The proposed method enables the calculation of the pure colorimetric information by removing the influence of the light leakage [21]. In the proposed method, nine parameters (XR, XG, XB, YR, YG, YB, ZR, ZG, and ZB) [21] are used to simulate the color information (x, y, Y) of any combination of the R, G, and B digital data. Here, (x, y) and Y represent the chromatic coordinates in CIE 1931 and luminance, respectively.

$$X = \int_{380}^{780} S(\lambda)R(\lambda)\bar{x}(\lambda)d\lambda \tag{7a}$$

$$Y = \int_{380}^{780} S(\lambda)R(\lambda)\bar{y}(\lambda)d\lambda \tag{7b}$$

$$Z = \int_{380}^{780} S(\lambda)R(\lambda)\bar{z}(\lambda)d\lambda \tag{7c}$$

Conventional color simulation methods use steady-state tri-stimulus values X, Y, and Z to simulate the color performance of the AMLCD. X,