CROSSTALK MODELING, ANALYSIS, SIMULATION AND CANCELLATION IN PASSIVE-TYPE STEREOSCOPIC LCD DISPLAYS

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ABSTRACT

Passive-type stereoscopic LCD display (or polarized 3D TV) generates 3D effect using quarter-wave patterned retarders and polarized glasses. However, passive-type stereoscopic displays are susceptible to an undesirable effect called ”crosstalk”, which degrades the 3D effect and causes increased eye strain and nausea. In this paper, crosstalk in passive 3D LCD is modeled, analyzed and simulated by implementing extended Jones matrix method. We present how the display intensity changes with viewing angles and simulate stereo images with crosstalk. Furthermore, a method of crosstalk cancellation based on linear programming in YCbCr domain is proposed. Results of our proposed method show that zero crosstalk can be achieved in passive 3D displays with less contrast loss compared with other methods.

Index Terms— 3D displays, passive-type, modeling, crosstalk cancellation

1. INTRODUCTION

Passive 3D LCD display shows the left-view and the right-view videos using polarized glasses and displays. ”Crosstalk” or ”ghosting” is the visual perception caused by the light leakage from one view to the other. It is the most annoying artifact as it reduces the 3D experience, causing eye strain and nausea. There is no standard mathematical definition of crosstalk in 3D displays. Andrew Woods lists different crosstalk definitions in [1]. Qualitatively, crosstalk is the phenomenon of the light leaking from one channel into the other so that the two views are not completely separated.

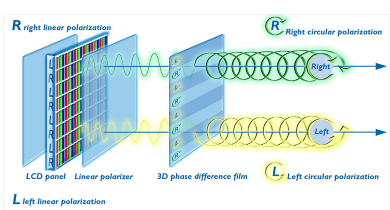

Fig. 1: Structure of circular polarization type 3D LCD [2]

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There are two contributions in this paper: crosstalk simulation and analysis in passive 3D LCD displays and an efficient crosstalk cancellation method which minimizes contrast loss. Crosstalk simulation is carried out using extended Jones matrix [3] and is significant for crosstalk cancellation as in passive 3D LCDs crosstalk is spatially dependent. The proposed crosstalk cancellation method uses linear programming in YCbCr domain, generating crosstalk-free stereo images with minimized contrast loss. Simulation results show that our method reduces crosstalk in passive 3D LCD with greater dynamic range compared to the existing methods based on subtractive crosstalk reduction in [4].

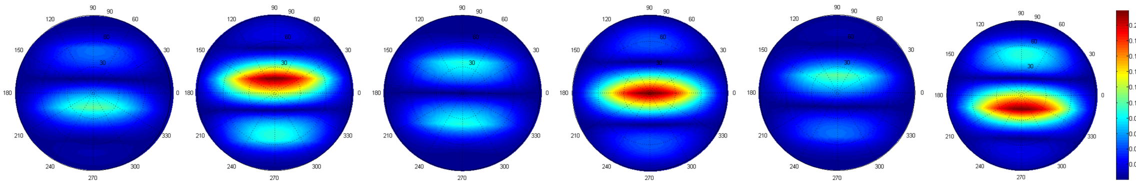
2. DISPLAY SIMULATION AND CROSSTALK ANALYSIS

2.1. How passive 3D LCD works

In passive-type 3D LCD displays, the screen is divided into the even field and the odd field where the even field consists of all the even-row pixels and the odd field odd-row pixels. The even field displays the left-eye images and the odd field displays the right-eye images, as shown in Fig. 1. Lights emitted from the even field (left-eye image) are left-hand circularly polarized and lights from the odd field (right-eye image) are right-hand circularly polarized. The left-eye lens of the passive 3D glasses only transmits the left-hand circularly polarized light, and vise versa for the right-eye lens. More explanation for circular polarization 3D LCD can be found in [5].

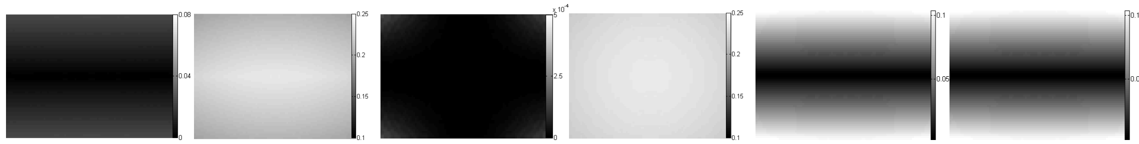
2.2. Full simulation of passive 3D LCD

Zhu et al. [6] and Yang et al. [7] modeled wide-view LCDs using extended Jones method and applied complementary films to the LCD to increase the viewing angle. Lee et al. [8], adopting the analytical solutions in Muller matrix form of biaxial material presented by [9], designed broad-band, wide-view, passive LCD configuration to reduce crosstalk. In this section, we use extended Jones matrix method [3] to model passive 3D LCD displays, simulate real stereo images with crosstalk in a passive 3D LCD, and characterize crosstalk using the mathematical model in [10]. The liquid



(a) black/white (b) white/black (c) black/white (d) white/black (e) black/white (f) white/black

Fig. 2: Light intensity (normalized) of left-eye view at different viewing angles.



(a) $I_l(0, 255)$ (b) $I_l(255, 0)$ (c) $I_l(0, 0)$ (d) $I_l(255, 255)$ (e) $C_l(0, 255)$ (f) $C_l(255, 0)$

Fig. 3: Simulation of screen display and crosstalk distribution in the left-eye view.

Fig. 4: Crosstalk simulation of real images (before crosstalk cancellation).

Table 1: Parameters used for IPS-LCD simulation [7]

Parameters	Description	Values
d_{LC}	LC Cell gap	$4\mu m$
$\theta_{pretilt}$	LC surface tilt angle	$1°$
$n_{LC,e}$	n_e of LC	1.5649
$n_{LC,0}$	n_o of LC	1.4793
n_{pe}	n_e polarizer	1.5+j0.0022
n_{po}	n_o polarizer	1.5+j0.000032
$n_{qw,e}$	n_e of $\lambda/4$ retarder	1.5606
$n_{qw,0}$	n_o of $\lambda/4$ retarder	1.4770

crystal (LC) panel of the LCD is specified as In-Plane Switching (IPS), which is one of the major configurations of liquid crystal in wide-view LCD. Unlike [8], which proposes novel design to reduce crosstalk, our goal is to simulate the current consumer 3D LCD and perform crosstalk cancellation using image-processing approach.

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix}_{out} = \mathbf{J} \cdot \begin{bmatrix} E_x \\ E_y \end{bmatrix}_{in} \tag{1}$$

$$\mathbf{J} = \mathbf{J}_{p,g} \cdot \mathbf{J}_{qw,g} \cdot \mathbf{J}_{qw,LCD} \cdot \mathbf{J}_{a,LCD} \cdot \mathbf{J}_{IPS} \cdot \mathbf{J}_{p,LCD} \tag{2}$$

Eq. (1) is the basic form of Extended Jones matrix method [3], where $\mathbf{J}$ is the 2 by 2 Jones matrix characterizing optical components such as LC. E_x and E_y are x and y polarization components of the light respectively. In Eq. (2), $\mathbf{J}$ is the cascade of the crossed linear polarizers in LCD: $\mathbf{J}_{p,LCD}$ and $\mathbf{J}_{a,LCD}$, LC panel: $\mathbf{J}_{IPS}$, patterned quarter-wave retarders: $\mathbf{J}_{qw,LCD}$, quarter-wave retarder in glasses: $\mathbf{J}_{qw,g}$, and linear polarizer in glasses: $\mathbf{J}_{p,g}$. Table 1 lists the parameters used for simulation. Details of extended Jones can be found in [3]. The implementation of extended Jones in passive-type 3D LCD displays including matlab codes can be found on our website [11]. Simulation of the light intensity in the left-eye view at different viewing angles are shown in Fig. 2 where the captions of the subplots specify the signals in the left-eye and the right-eye channels. Fig. 2(a, b) are results when shifting down the patterned retarder (PR) w.r.t the pixel, Fig. 2(c, d) when the PR and the pixel are aligned, Fig. 2(e, f) when shifting the PR up. The reason for this relative location change between the PR and the pixel is to reduce light leakage which is illustrated in "passive displays" of [12]. Our simulation results are consistent with the measured results in [2] and [12]. The light leakage in Fig. 2(b, d, f) is the main reason for crosstalk in passive 3D LCD displays.

2.3. Crosstalk modeling and analysis

For crosstalk analysis, we use the mathematical definition given in (3) [10], where C is crosstalk ratio, I is intensity, subscript l means the quantity is in the left-eye view (r for the right-eye view), and indices i and j are gray levels in the left-eye and the right-eye channels respectively. For the analysis, we use crosstalk between black and white in the left-eye view ($C_l(0,255)$ and $C_l(255,0)$) and assume the screen is in frontal view with the dimension of 66cm by 100cm, and assume the distance between the viewer and the screen is 2m.

$$C_l(i,j) = \frac{I_l(i,j) - I_l(i,i)}{I_l(j,j) - I_l(i,i)} \tag{3}$$

The results of the screen intensity simulation and crosstalk characterization are shown in Fig. 3, where Fig. 3(a-d) are space-dependent intensities (normalized) for calculating $C_l(0,255)$ and $C_l(255,0)$ in Fig. 3(e, f). $C_l(0,255)$ and $C_l(255,0)$ reach the highest value of 10% at the upper and lower edges of the screen and reach the lowest of 0.3% at the center location of the screen. Thus from our analysis, when at frontal view, crosstalk is lower in the central band of the screen and higher near the upper and lower edges of the screen. This result is consistent with the "3D contrast" in [2].

Furthermore, real stereo images with crosstalk simulation are shown in Fig. 4 where we observe that crosstalk is most visible in regions near the upper and lower edge of the screen with greater gray scale difference between the left-eye and the right-eye channels.

3. CROSSTALK CANCELLATION

3.1. Previous work

Most of the image-processing based techniques for crosstalk cancellation are designed for 3D displays using active shutter glasses, and they [13] [14] [15] [16] follow the subtractive crosstalk reduction method in [4] by J.S. Lipscomb. The idea of this method is to subtract from the input intensity the amount of crosstalk so the output intensity is compensated and crosstalk is cancelled out. To constrain the subtracted input intensity to be non-negative, the original lowest gray scale (background level, BG) in the image has to be increased and this causes contrast loss in the output image.

However, methods based on subtractive cancellation can't guarantee crosstalk-free results in cases where one channel needs subtraction while the other needs to be raised up and thus the normalized intensity is possible to exceed 1. The unattainable input intensity will yield crosstalk. In our method, both BG decrement and foreground level (FG) increment are allowed simultaneously thus crosstalk-free output is guaranteed with attainable input. Furthermore, our results show that allowing adjustment in both the BG and FG level yields less contrast loss compared to raising BG level alone. Also, simulation of light transmission in the previous session contributes to more efficient crosstalk reduction in that crosstalk distribution is spatially dependent and that only pixels contributing the most to crosstalk are used for crosstalk cancellation.

3.2. Proposed method

We formulate this problem of minimizing the contrast loss while ensuring zero crosstalk and attainable modulated input signals into a linear programming problem as:

$$\begin{aligned}
&\underset{b_L, f_L, b_R, f_R}{\text{minimize}} \; b_L + f_L + b_R + f_R \\
&\text{subject to} \\
&\begin{bmatrix} 0 \\ 0 \end{bmatrix} \preceq \mathbf{T}_i^{-1} \cdot \begin{bmatrix} I_{Li} \cdot (1 - b_L - f_L) + b_L \\ I_{Ri} \cdot (1 - b_R - f_R) + b_R \end{bmatrix} \preceq \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \\
&i = L_{min}, L_{max}, R_{min}, R_{max}; \\
&0 \le b_L, f_L, b_R, f_R \le 1; \\
&0 \le b_L + f_L, b_R + f_R \le 1;
\end{aligned} \tag{4}$$

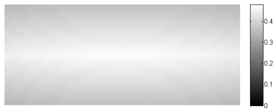
$$\mathbf{T}_i = \begin{bmatrix} t_{LL,i} & t_{LR,i} \\ t_{RL,i} & t_{RR,i} \end{bmatrix} \tag{5}$$

In (4), $\mathbf{T}_i$ is the 2 by 2 transmission matrix at pixel i and is defined in (5). Element $t_{LR,i}$ in (5) is the percentage of the light transmitted from the right-eye channel through the left-eye lens. The other elements in (5) are similarly defined. Given $\mathbf{T}_i$, and let $[I_{Li}, I_{Ri}]^T$ be the vectorized input signal from the left-eye and the right-eye channels, then $\mathbf{T}_i \cdot [I_{Li}, I_{Ri}]^T$ becomes the output signal received by the two eyes.

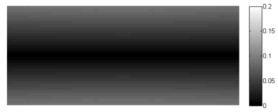
It's obvious that the off-diagonal terms in $\mathbf{T}_i$ induce crosstalk. A simple way to cancel out crosstalk is to change the input signal into $\mathbf{T}_i^{-1} \cdot [I_{Li}, I_{Ri}]^T$ so that the output becomes $\mathbf{T}_i \cdot (\mathbf{T}_i^{-1} \cdot [I_{Li}, I_{Ri}]^T)$. However, $\mathbf{T}_i^{-1} \cdot [I_{Li}, I_{Ri}]^T$ as the input signal could be unattainable ($\preceq \mathbf{0}$ or $\succeq \mathbf{1}$). Thus we need to find the input signals $[I_{Li}, I_{Ri}]^T$ with pixel indices $i = L_{min}, L_{max}, R_{min}, R_{max}$ that generate the lowest and the highest unattainable values in both the left-eye and the right-eye channels respectively. Then we shift and scale all input signals so that $\mathbf{T}_i^{-1} \cdot [I_{Li,new}, I_{Ri,new}]^T$ is attainable. In (4), take the left-eye signal for example, $I_{Li,new}$ is set as $I_{Li} \cdot (1 - b_L - f_L) + b_L$, where b_L is the background (BG) increment and f_L is the foreground (FG) decrement. The range of the output signal $\mathbf{T}_i \cdot (\mathbf{T}_i^{-1} \cdot [I_{Li,new}, I_{Ri,new}]^T)$ becomes $[b_L, 1 - f_L]$ (for all i). In (4), b_R is BG increment and f_R is the FG decrement value for the right-eye signals respectively.

However, shifting and scaling lower the contrast. To minimize the contrast loss, the objective function in (4) returns the values for b_L, f_L, b_R, f_R that best preserve the dynamic range of the original images. The first constraint in (4) in vector inequality form is to ensure attainable modulated input signal and, the second and the third constraints in (4) are to confine the BG increment and FG decrement values within a reasonable range.

$\mathbf{T}_i$ is pixel dependent and its elements are results in our display simulation in the previous session: $t_{LL,i}$ is the transmittance from the left-eye channel (even field) to left-eye lens , $t_{LR,i}$ from right-eye channel (odd field) to the left-eye lens transmittance. We assume $\mathbf{T_i}$ is symmetric. Calculating $t_{LL,i}$ and $t_{LR,i}$ for all pixels in both channels result in Fig. 5(a, b) which only have half of the original screen height in that they are either even-column pixels or odd-column pixels.



(a) Even field in left view



(b) Odd field in left view

Fig. 5: Simulation of transmission of the left-eye ($t_{LL,i}$) and the right-eye ($t_{LR,i}$) pixels after the left-eye lens.

For crosstalk cancellation in color images, we can optimize in the RGB channels separately and choose the parameters (b_L, f_L, b_R, f_R) that produce the greatest contrast loss but ensure zero crosstalk, and apply them to all three color channels. The other way is to separate the luminance and the chrominance channels apart, and keep the chrominance unchanged but only modulate the luminance channel. The advantages for the latter method is that color is better preserved and crosstalk cancellation in luminance is more efficient. Ref. [13] performs crosstalk cancellation in YCbCr domain and [16] uses CIELAB representation of the color image. We implement our crosstalk cancellation algorithm in YCbCr domain.

$$I = ((Y - 16)/235 + b)^{\gamma}; \tag{6}$$

Note in (4) that $I_{L,i}, I_{L,i}, b_L, f_L, b_R, f_R$ are all normalized light intensities but not the gamma encoded gray scales. Thus we need to first convert the RBG signal into YCbCr, leave the chrominance signal unchanged and convert Y into intensity. Eq. (6) converts Y into intensity, where b is the background display intensity which is set as 0 and γ is set as 2.2.

4. RESULTS AND DISCUSSION

Fig. 6 shows the simulation results of crosstalk cancellation with several methods. The stereo images used can be found in [17]. Fig. 6(a, b) show results of crosstalk cancellation in RGB channels, where crosstalk becomes invisible but contrast drops and images are bluish (color shift). Fig. 6(c, d) are results of crosstalk cancellation in YCbCr domain and with BG increment alone, where the contrast is boosted significantly with no color shift. Fig. 6(e, f) show results from the proposed algorithm in (4) which allows both BG increment and FG decrement. We can see that the dynamic range is furtherly boosted compared with Fig. 6(c, d), and they are also without color shift in the sense that the original chrominance: Cb and Cr are retained.

The dynamic range of the images after being applied with the three different crosstalk cancellation methods is shown in Fig. 7. We can see that in most cases, such as ”Aloe”, ”Flowerpots”, there is significant gain in contrast. Moreover, for cases that our proposed method doesn’t have obvious improvement, the other two methods already have good enough dynamic range in gray scale.

(a) RGB, left

(b) RGB, right

(c) YCbCr, BG only, left

(d) YCbCr, BG only, right

(e) YCbCr, BG & FG, left

(f) YCbCr, BG & FG, right

Fig. 6: Results of crosstalk cancellation in left-eye and right-eye images. (a, b): RGB method, (c, d): YCbCr method with BG increment only, (e, f): YCbCr method with BG increment and FG decrement (proposed).

5. CONCLUSION

Using Extended Jones matrix method, we are able to model and characterize crosstalk in passive-type 3D LCD displays and simulate the 3D screen with crosstalk. The results of screen simulation at different viewing angles are consistent with the measured results in [2] and [12]. Furthermore, stereo images with crosstalk simulation are applied with the proposed crosstalk cancellation method, and the results show that our method can produce crosstalk-free images in the display with the lowest contrast loss.

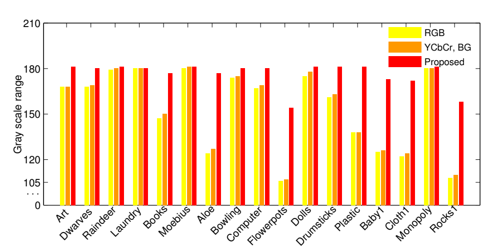


Fig. 7: Dynamic range after crosstalk cancellation

6. REFERENCES

[1] A. J. Woods, “How are Crosstalk and Ghosting defined in the Stereoscopic Literature,” in *SPIE Stereoscopic Displays and Applications XXII*. SPIE, 2011, vol. 7863.

[2] T. Leroux and P. Boher, “Characterization of autostereoscopic and polarization based 3D displays: a common approach,” in *IMID 2009 DIGEST*. IMID, Seoul, Korea, Oct 2009.

[3] A. Lien, “A Detailed Derivation of Extended Jones Matrix Representation for Twisted Nematic Liquid Crystal Displays,” *Liquid Crystals*, vol. 22, pp. 171–175, Aug 1997.

[4] J.S. Lipscomb and W.L. Wooten, “Reducing Crosstalk between Stereoscopic Views,” in *Proceedings of SPIE Stereoscopic Displays and Virtual Reality Systems*. SPIE, 1994, vol. 2177, pp. 92–96.

[5] Y. Yoshihara, H. Ujike, and T. Tanabe, “3D Crosstalk of Stereoscopic 3D Display using Patterned Retarder and Corresponding Glasses,” Int. Display Workshop, Kyoto, Japan, 2008, 3Dp-5, pp. 1135–1138.

[6] X.Y Zhu, Z.B. Zhe, and S.T Wu, “Analytical Solutions for Uniaxial-Film-Compensated Wide-View Liquid Crystal Displays,” *Journal of Display Technology*, vol. 2, No.1, pp. 1551–319X, Mar 2006.

[7] D.K. Yang and S.T. Wu, *Fundamentals of Liquid Crystal Devices*, Jone Wiley & Sons Ltd.

[8] C.T Lee and H.Y. Lin, “Ultra-wide-view patterned polarizer type stereoscopic LCDs using patterned alignment,” *Optics Express*, vol. 20, No.2, pp. 1700–1705, Jan 2012.

[9] Y.C Yang and D.K. Yang, “Analytic expressions of optical retardation of biaxial compensation films for liquid crystal displays,” *Journal of Optics A: Pure Appl.*, vol. 11, no. 10, pp. 105502, Oct 2009.

[10] S. Shestak, D. Kim, and S. Hwang, “Measuring of Gray-to-Gray Crosstalk in a LCD Based Time-Sequential Stereoscopic Display,” SID 2010, Seattle, 2010, pp. 132–135.

[11] M. Zeng, “Results of passive 3D LCD simulation,” `http://tinyurl.com/videoprocessing-mzeng-results/`.

[12] P. Boher and T. Leroux, “Optical Characterization of Different Types of Stereoscopic 3D Displays,” in *Exhibitor Forum SID Conference*. The Society for Information Display, May 19 2011.

[13] C. Doutre and P. Nasiopoulos, “Optimized contrast reduction for crosstalk cancellation in 3D displays,” IEEE,3DTV Conference 2011, Antalya, Turkey, May 2011.

[14] T. Kim, J.M. Ra, J.H. Lee, S.H. Moon, and K.Y. Choi, “3D Crosstalk Compensation to Enhance 3D Image Quality of Plasma Display Panel,” *IEEE Transactions on Consumer Electronics*, vol. 57, pp. 1471–1477, Nov 2011.

[15] J. Konrad, B. Lacotte, and E. Dubois, “Cancellation of Image Crosstalk in Time-Sequential Displays of Stereoscopic Video,” *IEEE Transactions on Image Processing*, vol. 9, pp. 897–908, May 2000.

[16] F.A. Smit, R.V. Liere, and B. Frohlich, “Three Extensions to Subtractive Crosstalk Reduction,” in *IPT/EGVE*. Eurographics Symposium on Virtual Environments, 2007, pp. 85–92.

[17] D. Scharstein and R. Szeliski, “Stereo Dataset of 2006,” `http://vision.middlebury.edu/stereo/data/`.