Optimizing Time-Multiplexing Auto-Stereoscopic Displays With a Genetic Algorithm

Haowen Liang, Senzhong An, Jiahui Wang, Yangui Zhou, Hang Fan, Peter Krebs, and Jianying Zhou

***Abstract*—A figure-of-merit (FOM) of an auto-stereoscopic display system is introduced and adopted to characterize the system performance. This FOM takes into account of the ratio of the signal to the noise arising from the crosstalk from the adjacent channels as well as the brightness uniformity of viewing areas; hence, it is directly related to the glasses-free 3D viewing comfort. With a steadily improving FOM as a target, the genetic algorithm is applied to optimize the optical system, giving rise to substantially improved characteristics of an auto-stereoscopic display system. The numerical simulation is verified with an experiment of a multi-view auto-stereoscopic display unit. It is shown that the system can provide a high fidelity of the display effect with the crosstalk ratio being reduced from around 5% to nearly 1%, which is a very low value obtainable for an auto-stereoscopic system.**

***Index Terms*—3D display, auto-stereoscopic, crosstalk, figure of merit (FOM), genetic algorithm.**

I. Introduction

AUTO-STEREOSCOPIC displays can create 3D effect without requiring the observers to wear extra equipments such as glasses or helmets. A number of techniques were proposed to show parallax images by either spatial-multiplexing or time-multiplexing. By spatial-multiplexing, a parallax barrier or a lenticular lens array would degrade the 3D resolution despite separating an image into two views easily [1]–[3], while by time-multiplexing the backlight units (BLUs) turn on/off alternately with at least 120 Hz frame rate to preserve full-resolution [4]–[7]. It is proposed that a liquid crystal display (LCD) panel with a lenticular lens array and an active dynamic backlight unit (lenticular-active backlight unit, L-ABLU) is an effective time-multiplexing scheme not only to preserve full-resolution but also to generate multi-viewing zones [8]–[12].

Currently, the main technical issues in auto-stereoscopic displays are reduced resolution [13]–[15], high crosstalk [16]–[20], and the nonuniform brightness distribution in a viewing zone [21]–[23]. Individual parameters, such as crosstalk ratio, brightness uniformity in a viewing zone, the area of a viewing zone and the sweet spot, are applied to evaluate the 3D performance. However, any of these individual parameters is not sufficient to characterize glasses-free displays, and the adoption of a convenient parameter is necessary.

A figure-of-merit (FOM) is a quantity used to determine the relative utility for an optical device, such as the signal-to-noise ratio (SNR) in communication and the overlapping ratio in waveguide design [24]. In this paper, an FOM for auto-stereoscopic displays is defined. Various combinations of lens parameters in an L-ABLU system, including radius (R), height (h), pitch (P) and refractive index (n_g), generate different FOMs.

With the application of the genetic algorithm (GA) search, the best FOM and optimal L-ABLU structure can be determined, yielding "rectangular-like" viewing zones with low crosstalk as well as high brightness uniformity in each viewing zone, which is in contrast with the viewing zones with Gaussian shapes [14], [19], [25]. By measuring the intensity profiles, a good agreement between the simulation and the experiment is obtained. Therefore this optimized FOM would be a universally useful evaluation tool for auto-stereoscopic displays, which may serve as a design guideline for a time-multiplexing auto-stereoscopic system.

II. Theory

A lenticular based time-multiplexing auto-stereoscopic display (illustrated in Fig. 1) directs light of sub-BLUs to different directions, generating series of viewing zones so that the observer could perceive 3D effect in a number of positions. In order to provide comfortable 3D effect, a viewing zone oughts to be of a "rectangular-like" shape with low crosstalk and high brightness uniformity.

We introduce an FOM of an auto-stereoscopic system to describe the crosstalk from the adjacent channels as well as the shapes of viewing zones in the sweet spots It is related to the ratio of the integrated optical intensity (normalized intensity profile, $I(X)/I_{\max}(X)$) within the viewing zone to its value outside:

$$\mathrm{FOM} = \frac{\Sigma_v}{\Sigma_\infty - \Sigma_v} \tag{1}$$

$$\Sigma_v = \int_{X_s}^{X_s+W_v} I_{\mathrm{normalized}}(X)dX \tag{2}$$

$$\Sigma_\infty = \int_{-\infty}^{+\infty} I_{\mathrm{normalized}}(X)dX \tag{3}$$

where X_s is the starting position of the viewing zone. Generally an integral over X of the intensity profile $I(X)$ gives the power of an emitting light source. It is assumed that there is no loss of power transmission through the lens array. In (1)–(3), Σ_∞ is integral of the intensity profile in the whole space while Σ_{v} is

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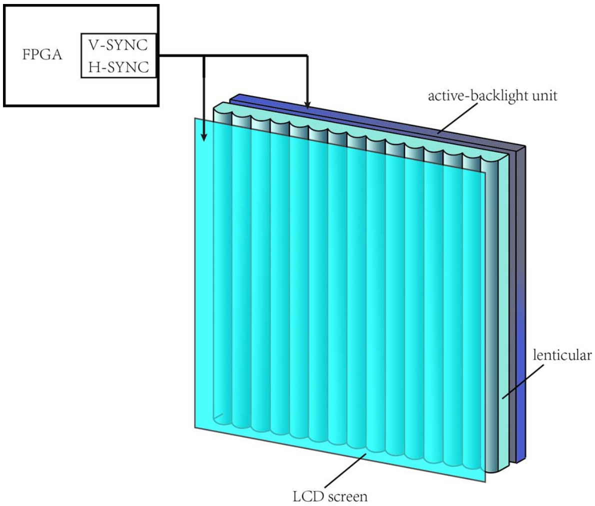

Fig. 1. General scheme of lenticular based time-multiplexing auto-stereoscopic display. It consists of an LCD screen and an L-ABLU structure (lenticular-active backlight unit).

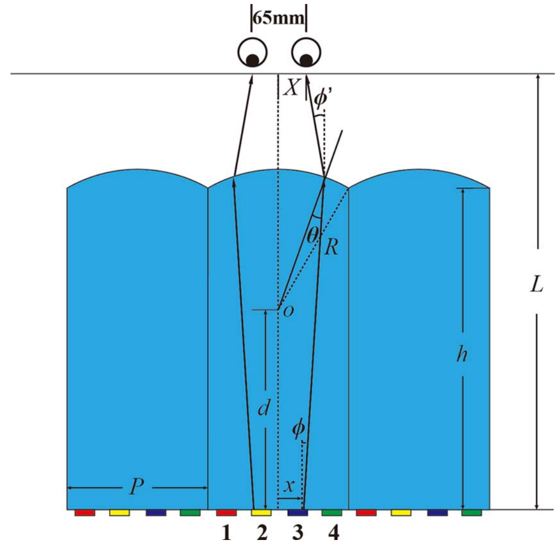

Fig. 2. Illustration of the ray-tracing in an L-ABLU structure.

the integral of the intensity profile within a viewing zone [W_v in Fig. 3(a)]. In an actual case, the total power emitted by a light source is a fixed value. Therefore Σ_∞ is a constant and the FOM is associated with Σ_v. A better FOM, or a larger Σ_v denotes that most of the emitting power concentrates in the viewing zone and the leakage of light is a small proportion, suggesting the crosstalk from the neighbouring zones being suppressed. The crosstalk ratio of the nth view zone in an N viewing zones case is described by

$$\text{Crosstalk Ratio} = \frac{\sum_{\substack{i=1\\ i\neq n}}^{N} I_i(X)}{\sum_{i=1}^{N} I_i(X)} \times 100\%. \tag{4}$$

As well, a better FOM tends to reshape the intensity profile of a viewing zone to have a "rectangular-like" shape. This can certainly improve the brightness uniformity of a viewing zone as well as reduce the leakage to the neighboring zones. Then the intensity profile of a viewing zone should be optimized into a "rectangle". The Cauchy–Schwartz inequality gives rise to a criteria to reach that goal:

$$\left|\int_a^b f(x)dx\right|^2 \leq (b-a)\int_a^b f^2(x)dx \tag{5}$$

where the inequality turns to be an equation where $f(x) = const$. In auto-stereoscopic displays, $I_{\text{normalized}}(X) \rightarrow const$ yields the nearly rectangular shape of a viewing zone. Inserting (2) in the left side of (5) we obtain

$$\Sigma_v^2 \leq W_v \int_{X_s}^{X_s+W_v} I_{\text{normalized}}^2(X)dX. \tag{6}$$

Equation (6) shows that Σ_v has an upper limited value and a larger Σ_v yields to require $I_{\text{normalized}}(X) \rightarrow const$, indicating a uniform auto-stereoscopic brightness distribution in a viewing zone. Therefore imporving the FOM helps to transform the viewing zone into a preferred shape.

The ray-tracing model is the usual method to simulate the intensity profile of a lenticular lens array based auto-stereoscopic display [26], [27]. One of the efficient ways to simulate the intensity profile is proposed in [26]. Equation (7) gives the eye-received intensity profile due to the sum of all light rays from a Lambertian sub-BLU through the lenticular lens array:

$$I_{\text{normalized}}(X) = \int_{x_s}^{x_s+W_p} dx \int_{d\phi_0}^{d\phi_M} d\phi \cos\phi\,\delta(X - G(\phi,x)) \tag{7}$$

$$\delta(X - G(\phi,x)) \Rightarrow (1/\pi)/[1 + (X - G(\phi,x))^2] \tag{8}$$

where $\phi_M = \tan^{-1}((P/2 - x)/h), \phi_0 = -\tan^{-1}((P/2 + x)/h), x_s$ is the starting position of the sub-BLU. $G(\phi,x)$ is obtained by (9)–(11) with ray-optics referred to [26]

$$\begin{aligned} G(\phi,x) =& x + (d + R\cos(\theta+\phi))\tan\phi \\ &- (L - d - R\cos(\theta+\phi))\tan\phi' \end{aligned} \tag{9}$$

$$\begin{aligned} \theta+\phi =& \cos^{-1}\left(\left[\frac{1}{(1+\tan^2\phi)}\right]\left[-\frac{\tan\phi(x + d\tan\phi)}{R}\right.\right. \\ &\left.\left.+\sqrt{(1+\tan^2\phi) - (\frac{(x+d\tan\phi)}{R})^2}\right]\right) \end{aligned} \tag{10}$$

$$\phi' = \sin^{-1}(n_g\sin\theta) - (\theta+\phi) \tag{11}$$

where R is the radius of a lenticular lens tip, P is the pitch of a lenticular lens and L is the viewing distance. d, h, θ, ϕ and ϕ' are shown in Fig. 2.

III. Results and Discussion

For an auto-stereoscopic display, the parameters $R, d, h, 2\sigma$ are usually obtained by traditional geometrical optics design [9], [12], [21]:

$$W_p + 2\sigma : 65 = d : L - d \tag{12}$$

$$4W_p + 8\sigma : P = d : L - d \tag{13}$$

$$R/n_g = 2W_p + 4\sigma \tag{14}$$

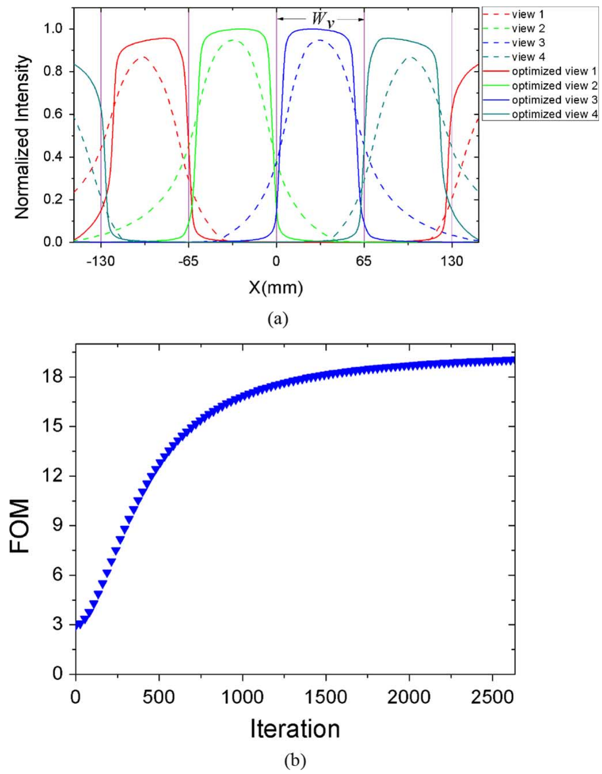

Fig. 3. (a) Intensity profiles of the four main viewing zones before optimization (dash lines) and after optimization (solid lines). (b) Evolution of FOM in the optimization process.

where 2σ is the gap between each sub-BLU. Since the crosstalk is mainly contributed by the adjacent lens [9], [14], [26], a three-lens model is sufficient to represent a periodical L-ABLU structure in this case. The auto-stereoscopic sweet spot is set at the viewing distance $L = 500$ mm from the LCD screen. The lens is made of glass with the refractive index $n_g = 1.511$ and the width of each sub-BLU is $W_p = 2$ mm. From (12)–(14) we obtain $d = 19.23$ mm, $2\sigma = 0.6$ mm, $P = 10.4$ mm and $R = 7.86$ mm. The dash lines in Fig. 3 show the result of simulation with the ray-tracing model of a three-lenticular-lenses model illustrated in Fig. 2.

In this case, the FOM defined in (1) is 2.84. An optimized FOM gives ideal auto-stereoscopic viewing areas as well as the optimal combination of L-ABLU structural parameters. To optimize the FOM, a GA search is applied. Setting the FOM as the target, the algorithm calculates the FOM of different combinations of structural parameters automatically and records the larger FOM until it finds the largest value in the searching range, hence defining the optimal combination. The optimized FOM is 18.54, giving the intensity profile in the solid lines in Fig. 3. The optimized structural parameters are $d = 17.3$ mm, $2\ \sigma = 0.22$ mm, $P = 8.88$ mm and $R = 9.0622$ mm with W_p and n_g being constrained to be constant ($W_p = 2$ mm and $n_g = 1.511$). The evolution of the FOM in the optimization algorithm is shown at Fig. 3(b).

To verify the optimal design validity, an L-ABLU system is set up. The L-ABLU consists of a lenticular lens array with the structural parameters obtained from the optimized simulation. The lenticular lens array is established by three K9 glass-based cylindrical lenses as the model above. Each lenticular lens has a group of four lighting strips 1–4 corresponding to four viewing

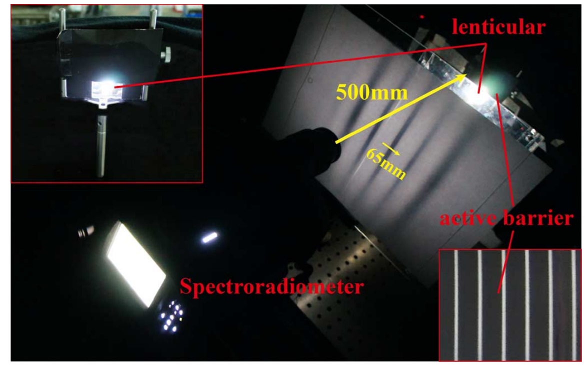

Fig. 4. Experimental setup.

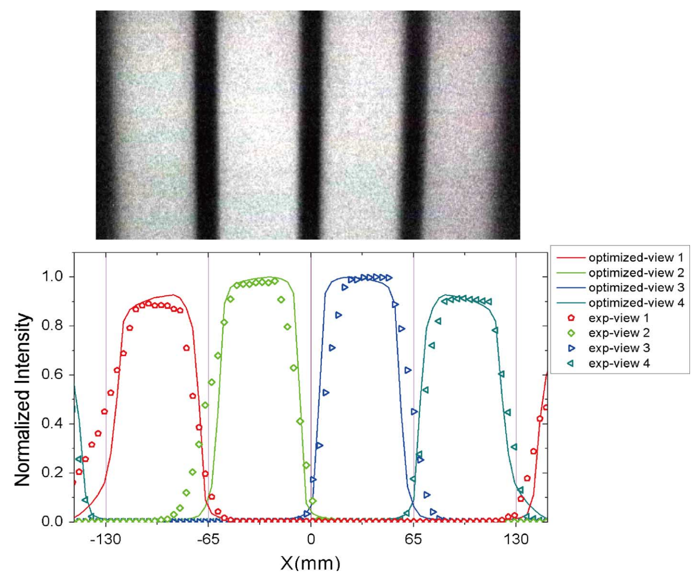

Fig. 5. Four main viewing zones in the experimental setup (up). The comparison between the result of simulation (solid lines) and experimental result (dots) is also shown.

zones. In an actual application, the active barrier can be synchronized with the LCD screen to generate black and white lighting strips sequentially. For a multi-viewer case, the refreshing rate of the LCD for a four-viewing-zones module should be at least 240 Hz to make it comfortable for the viewers, while for a single-viewer case with the eye-tracking the refreshing rate of the LCD could be just 120 Hz. Driven by 240 Hz, the group of sub-BLU strips 1 turn on for 1/240 second in a 60 Hz frame, and the remaining groups of strips 2–4 share the other three 1/240-second sequentially. With eye-tracking, two adjacent groups of strips would be chosen to turn on so that the chosen groups of strips share 1/120 second per 60 Hz frame respectively.

A SpectraScan Spectroradiometer (Photo Research, Inc., PR-655) is used to measure the intensity profile of the L-ABLU system. The distance from the Spectroradiometer to the center of LCD is 500 mm, which is the comfortable viewing distance for a small panel display system. The distance between the centers of two central sweet spots is 65 mm (the average inter-pupillary distance). Measurements of the horizontal distance are from -150 mm to 150 mm to cover the four main viewing zones (shown in Fig. 4).

Fig. 5 shows the comparison of the numerical result with the experimental data. The main viewing zones are also shown in

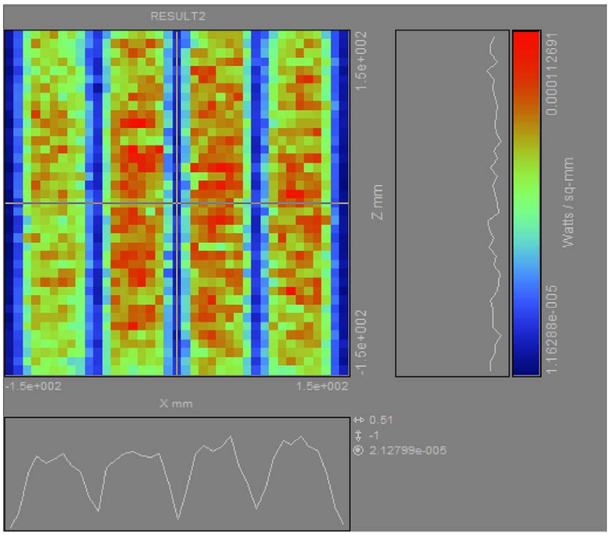

Fig. 6. L-ABLU simulating result obtained from ASAP™. A 21-pitches lenticular lens array and twenty-one groups of four lighting strips with optimized parameters in this paper are used in the simulation.

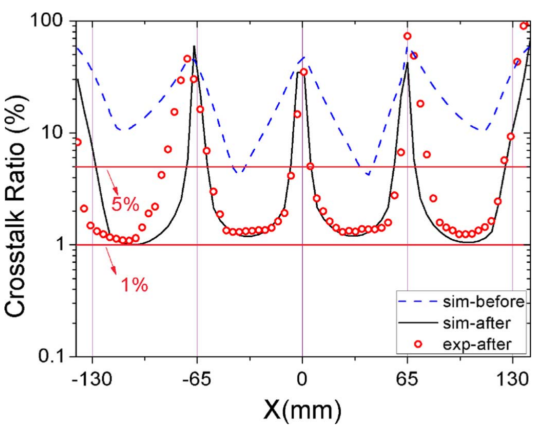

Fig. 7. Crosstalk ratio distribution in four main viewing zones (without LCD screen). After optimization the crosstalk ratio stays low in each viewing zone (black solid line) rather than being very sensitive to the horizontal position before optimization (blue dash line). The experimental result (dots) matches our optimized numerical result.

Fig. 5. Overall, the agreement between the theory and the experiment is good. A simulation obtained by commercial ray-tracing software ASAP™ (Breault Research Organization, Inc.) is also illustrated in Fig. 6. The results of simulation are also consistent with the experimental result.

To further confirm the FOM helps to improve auto-stereoscopic displays quality, the traditional crosstalk ratio defined in (4) is reapplied. The comparison of the crosstalk ratio (in a logarithmic scale) distributions of the numerical result before and after optimization with the experimental result is also depicted in Fig. 7. The crosstalk ratio was shown to be substantially improved from about 5% to nearly 1%. More significantly, the crosstalk ratio is not sensitive, and it remains a low value within each viewing zone. Therefore the 3D viewing effect is improved. Such distribution of crosstalk ratio helps generating continuous viewing zones. Fig. 8(a) and (b) illustrate the image quality with the same panel in normal 2D display mode and auto-stereoscopic mode. Both pictures are captured

(a) (b)

Fig. 8. Image quality in (a) 2D mode and (b) auto-stereoscopic mode.

at the right position and there is no hazardous degradation of image quality in both cases. Because of the careful design of our system, the flipping between the four views is not obvious. Also with eye-tracking the flipping can be synchronized with LCD pictures. Therefore this optimization does help to improve the display quality in both multi-view auto-stereoscopic displays and eye-tracking two view point auto-stereoscopic displays, as demonstrated recently in [28].

IV. Conclusion

An FOM for an auto-stereoscopic display system is introduced and adopted to characterize the system performance. With a steadily improving FOM as a target, the genetic algorithm searches the optimal structural parameters of a lenticular-active backlight unit. The optimized FOM reduces the crosstalk ratio from about 5% to around 1% in each viewing zone. Furthermore, each viewing zone has a "rectangular-like" shape of intensity profile showing good brightness uniformity of the display. Experimental results are found to be in a good agreement with the simulation, hence demonstrating the feasibility to significantly improving the existing glasses-free 3D display.

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