Adaptive Crosstalk Reduction Method in Eye-Tracking Stereoscopic Three-Dimensional Displays Using Color Similarity and Inverse Filter

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Abstract
We propose a method to reduce crosstalk for stereoscopic 3D displays using color similarity and inverse filter. For the pixels at boundary of two views, gray level is adjusted based on the color similarity between left and right images. In addition, an inverse filter is used to compensate brightness of left and right images considering crosstalk levels. The feasibility and effectiveness of the proposed method have been verified based on real-time shaders implementation.

Author Keywords
Three-dimensional (3D) Display; Light Field Display; Crosstalk; Eye-tracking; Inverse Filter

1. Introduction
Recently, significant efforts have been directed toward the commercialization of 3D displays. The majority of these displays are of the 2D/3D convertible type, utilizing switchable optics such as liquid crystal lenses. However, the fundamental principle behind their 3D image generation remains consistent with that of non-switchable lenticular lens-based systems, as illustrated in Figure 1. Advances in hardware technologies, including low-latency eye-tracking and high-performance graphic rendering, have further accelerated the readiness of 3D display technology for commercial applications.

At the repeated boundary regions between the left and right views on the display plane, leakage light is directed to the undesirable opposite eyes. This phenomenon makes viewers to perceive doubled images to each eye, which is known as 3D crosstalk [1]. A common approach to mitigate the crosstalk involves reducing the gray levels of pixels near the boundary regions [2]. However, it is important to note that this method often causes side effects, including a decrease in luminance and the appearance of color noise patterns. In other approaches, researches has been reported to address 3D crosstalk by introducing a crosstalk concealer [3], and disparity adjustment [4]. However, these two methods have limitations as they have risks to distort the originality of images by generating newly created images, such as creating concealers in areas of light bleeding or adjusting the disparity of input images. Meanwhile, studies on optimizing hardware such as pixel masks and triplet lenticular lenses for reducing crosstalk have been actively carried out [5,6]. This method has a limitation in its general application as it requires additional layers or lenses.

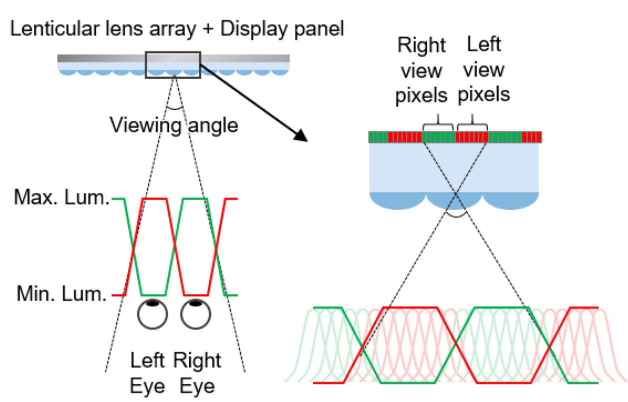

Figure 1. Schematic diagram of 2-view autostereoscopic three-dimensional displays.

To minimize crosstalk while avoiding these artifacts as much as possible, we propose applying the gray-level reduction method with varying intensities based on the color similarity that is calculated by comparing colors of the left and right images. This approach builds on the observation that crosstalk becomes more noticeable as the contrast in color increases, aiming to maximize the reduction effect while minimizing image quality degradation. Additionally, an inverse filter—a method that adjusts the gray scales of the image in advance to account for potential crosstalk—is employed. The inverse filter will be particularly effective in reducing crosstalk in the central regions of each view to add up the effect of crosstalk correction. We also developed a program implementing this algorithm in real-time and conducted experiments to verify its feasibility.

2. Principle
The proposed method in this study consists of two algorithms, depending on which regions of the viewmap are targeted:

- Adjusting gray scale of the pixels based on color similarity in the boundary regions of the viewmap
- Pre-processing potential crosstalk in advance in the central regions of the viewmap

This section provides a detailed explanation of these methods including their real-time implementation for operation on the actual 3D display.

Gray Adjustment Based on Color Similarity: This method builds upon the conventional approach of lowering the gray scale in the boundary regions among adjacent views. The regions are highlighted in gray in Figure 2. This approach can have a great enhancement by varying the adjustment magnitude based on the color similarity between the left and right images. For instance, if the pixels in the left and right images at the same position have similar colors, the perceived crosstalk is expected to be minimal, requiring less compensation. Conversely, if the color difference between the pixels is significant, the amount of perceived crosstalk will be higher, which means greater adjustment to the gray scale will be needed. This approach reduces the excessive image transformation while minimizing artifacts. This is because, in general, the areas that need to be expressed in 3D or have high color differences across the entire image account for only a small portion.

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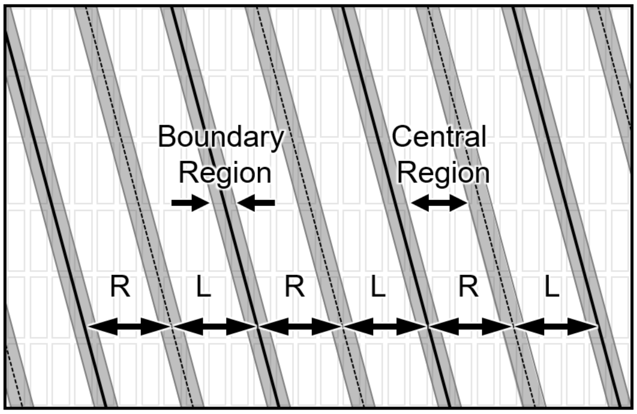

Figure 2. Two distinct crosstalk reduction methods are utilized depending on the regions: (a) gray adjustment based on color similarity is applied to the pixels at boundary regions among different views, and (b) inverse filter method is applied to the pixels at the central regions of views.

To implement this method, quantification is needed to evaluate the color similarity between left and right images. Numerous ways to compute color similarity can be employed, none of which are absolute; the method depends on the display performance, the characteristics of optical components, and the intention of system designer. A simple approach is to compare each gray level of images. Furthermore, the luminance ratio of each red, green, and blue pixel can be considered so that contrast can be reflected as a weighting factor to evaluate color similarity. Given these considerations, the equation utilized in this paper is derived under the assumption of an 8-bit color system as follows:

$$\text{Color Similarity} = 1 - \frac{\sqrt{0.3 \times (R_1 - R_2)^2 + 0.59 \times (G_1 - G_2)^2 + 0.11 \times (B_1 - B_2)^2}}{255} \quad (1)$$

(R_1, G_1, B_1) and (R_2, G_2, B_2) stand for the red, green, and blue gray scales of arbitrary two pixels, respectively. It is important to note that the choice of formula is not definitive and may vary depending on the intended purpose. Using the Equation 1, a color similarity map can be generated as shown in Figure 3, where pixels with identical gray levels yield a value of 1, and those ranging from full white to full black yield a value of 0. These values are normalized multipliers that can be directly applied by multiplying them with the original image.

This method is applied to the boundary regions of the viewmap, and the size of the applied area is appropriately determined depending on the situation. For instance, applying the adjustment to 10% of the boundary minimizes the decrease in luminance and color noise but may result in less effective crosstalk reduction. On the other hand, wider application such as 40% achieves better crosstalk reduction performance but may introduce noticeable artifacts. Figuring out the optimal ratio has remained a subject for further study yet. We assume that it depends on the specifications of the 3D display system and the characteristics of the images being used.

Inverse Filter: Inverse filter is additionally applied to the first method to enhance crosstalk reduction effect. Main target areas are central regions of each view, where the color similarity method does not work. This is a sort of pre-processing method by anticipating or measuring crosstalk of the display (e.g. 5 %) and adjusting gray levels of the left and right images as much as the crosstalk in advance [7].

$$\begin{cases} Img^P_{Left} = Img^S_{Left} + \gamma Img^S_{Right} \\ Img^P_{Right} = \gamma Img^S_{Left} + Img^S_{Right} \end{cases} \quad (2)$$

Img^P_{Left} and Img^P_{Right} represent the images perceived by an observer from the left and right images respectively, while Img^S_{Left} and Img^S_{Right} are the corresponding images displayed on a screen. As indicated in the equation, the perceived image is expressed as a weighted sum of the left and right images shown on the screen, which demonstrates the influence of the crosstalk coefficient γ determined by the hardware specifications of the 3D display. By preemptively reflecting the impact of crosstalk in Equation 2 to calculate Img^S_{Left} and Img^S_{Right}, we obtain as follows:

$$\begin{cases} Img^S_{Left} = \frac{1}{(1-\gamma^2)}(Img^P_{Left} - \gamma Img^P_{Right}) \\ Img^S_{Right} = \frac{1}{(1-\gamma^2)}(-\gamma Img^P_{Left} + Img^P_{Right}) \end{cases} \quad (3)$$

Real-time Implementation: In order to evaluate the efficacy of the proposed method, we implement the proposed method into both OpenGL and DirectX11 shaders for real-time processing and enhanced adaptability in potential future applications. By embedding the algorithm during the generation of the final viewmap image, we can utilize the pixelwise data of the left and right images already used in the process and make seamless integration possible. Furthermore, any pre-processing of the original image or pre-generating of extra images is not required, optimal performance and efficient use of memory resources are guaranteed.

(a) (b) (c) (d)

Figure 3. Examples of generating the color similarity maps: (a) Left perspective view image, (b) right perspective view image, (c) color similarity map of left image, and (d) color similarity map of right image. In color similarity maps, brighter areas indicate where the left and right images have similar colors; darker areas indicate where they have different color.

3. Experimental Results

We conducted experiments to verify the feasibility of the proposed technique by comparing its application before and after implementation. The specifications of the equipment used in the experiments are shown in Table 1.

Table 1. Specifications of experimental devices

Lenticular lens array		Display	
Pitch	100 LPI	Display size	27 inches
Slant angle	16˚	Resolution	3840×2160

Figure 4 shows the experimental results. We used two pairs of 3D SBS images in the experiment. Figure 4 (a) shows the results when using only typical 3D rendering. A planet-shaped ghost image appears on the left side of the main image. On the other hand, with our proposed crosstalk reduction method in Figure 4(b), it can be observed that the ghost almost disappears. In Figure 4(c), crosstalk image also appear as a bold curved line; as shown in Figure 4(d), they are significantly reduced by the proposed method. It can be observed that perceptual crosstalk is considerably reduced with minimal side effects – rarely perceptible decrease in luminance and barely noticeable color noise. In Figure 4(b), the luminance of the boxed area was measured to be approximately 96 % of the luminance in Figure 4(a). Considering that the typical crosstalk levels are below 5 %, it can be concluded that the luminance reduction is minimal. It is noted that the luminance was measured to be about 80 % with one of the most widely known methods to reduce crosstalk in [2]. As expected, in areas with no color similarity differences, the luminance was preserved without brightness degradation.

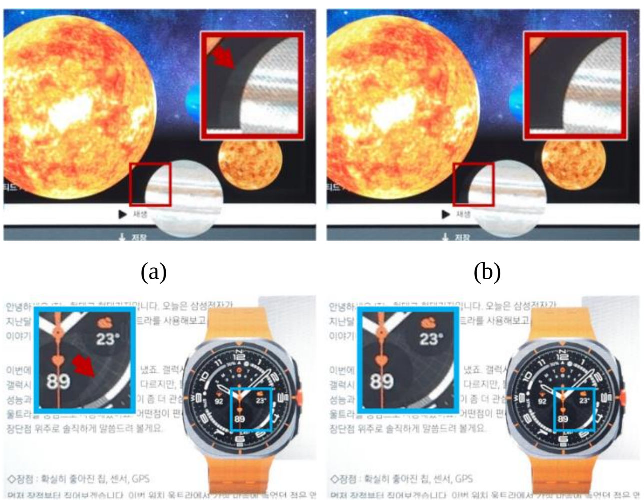

Figure 4. Two pairs of images for side-by-side 3D are used to conduct the experiments for verifying the feasibility of our proposed crosstalk mitigation method. (a), (c) When using typical 3D rendering without any crosstalk reduction method, ghost image appears. (b), (d) With the proposed crosstalk reduction technique, it cannot be observed that the ghosts are significantly reduced.

similarity differences, the luminance was preserved without brightness degradation.

We also evaluated the execution speed by measuring the process time on both high-end (RTX 4090) and low-end (GTX 1650) GPUs. With the algorithm turned on or off, there was no significant difference in speeds observed on either GPU. High-end GPUs achieved an average rendering rate of over 3,000 frames per second regardless of the algorithm's status. Low-end GPUs experienced an average delay of only about 0.3 ms when executing the new algorithm compared to the conventional approach. Despite this slight increase in latency, overall performance remains satisfactory, consistently reaching frame rates above 120 Hz in typical usage scenarios.

4. Impact

Crosstalk is one of the fundamental factors that degrade the quality of 3D displays, significantly contributing to visual fatigue which diminishes consumer preference for 3D displays. Addressing this issue is essential for the continued development and acceptance of 3D display technologies.

Traditionally, highly effective efforts to mitigate crosstalk have focused on hardware-based solutions. In contrast, the proposed solution in this paper offers a software-based approach, making it potentially easier to implement on existing systems. Furthermore, as the computational processing load is minimal and real-time implementation becomes feasible, it is expected that the proposed method can be widely and quickly applied. In conclusion, we believe that the proposed method will largely contribute the expansion and growth of the 3D display market.

5. References

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