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Crosstalk Minimization Method for Eye-tracking-based 3D Display

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Abstract. *In this article, the authors present an image processing method to reduce three-dimensional (3D) crosstalk for eye-tracking-based 3D display. Specifically, they considered 3D pixel crosstalk and offset crosstalk and applied different approaches based on its characteristics. For 3D pixel crosstalk which depends on the viewer's relative location, they proposed output pixel value weighting scheme based on viewer's eye position, and for offset crosstalk they subtracted luminance of crosstalk components according to the measured display crosstalk level in advance. By simulations and experiments using the 3D display prototypes, the authors evaluated the effectiveness of proposed method.* © *2020 Society for Imaging Science and Technology.*
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1. INTRODUCTION

Autostereoscopic displays can present left and right perspective images to the viewer without wearing glasses, and multiview three-dimensional (3D) displays realize this function by endowing directionality to light rays from the display panel using an optical layer such as a lenticular lens or a parallax barrier. However, it has limited viewing range called sweet spot and it suffers from ghost image or even pseudoscopic images outside the region in which disparity of stereo image is inverted. Subjective quality of stereoscopic display is highly correlated with 3D crosstalk [1–3], which represents the ratio of unwanted light leakage from other image channel caused by incomplete isolation of left and right views to the original image signal, and this can be defined as

$$\text{Crosstalk}(\%) = \frac{\text{leakage} - \text{black level}}{\text{signal} - \text{black level}} \times 100. \tag{1}$$

To suppress crosstalk of an autostereoscopic display, various kinds of approaches were proposed. Subtractive crosstalk cancelation [4–7] is a simple and effective method to remove the ghost artifact by subtracting the crosstalk component from the image signal before displayed, and this can be applied to both stereo and autostereoscopic 3D displays. In this approach, contrast of input image can be scaled for the case that crosstalk is greater than image signal. Also, there are crosstalk reduction methods dedicated for multiview 3D display systems. In [8], the horizontal crosstalk component is removed by fractional view mapping and crosstalk induced by slanted lens structure is removed by inverse filtering. In the work of [9], the crosstalk between the neighboring view images is eliminated by correcting the intensity values of subpixels in synthetic images.

Compared to multiview 3D display, eye-tracking-based 3D display can provide a 3D image of higher quality with low crosstalk over a wider viewing range by optimizing pixel resources to a certain position where the observer is located although it requires additional camera and eye-tracking module. Previously, we proposed a crosstalk reduction method for eye-tracking-based multiview display [10], where the inter-view crosstalk and color artifact caused by the slanted lenticular lens are reduced by colorwise normalization of brightness in the horizontal direction. In this article, we present a novel crosstalk reduction method for eye-tracking-based 3D display. We applied two kinds of specific methods according to the source of 3D crosstalk using the eye position information from the eye-tracking module. In Section 2, we explain the characteristics of 3D crosstalk in eye-tracking-based 3D display systems, and proposed respective crosstalk methods in Section 3. In Section 4, we present simulation and experimental results using our 3D display prototypes (10.1” 3D tablet, 31.5” 3D monitor).

2. 3D CROSSTALK FOR EYE-TRACKING-BASED 3D DISPLAY

In eye-tracking-based 3D display, light rays generated from subpixel position through the optical layer such as parallax barrier and lenticular lens are merged at viewer's eye position using the eye-tracking information and each subpixel value is assigned by 3D rendering process to make left and right image contents to be seen separately. Figure 1 is an example of a merged luminance profile for eye-tracking-based 3D display measured from our 10.1” 3D tablet prototype. Each curve in the upper figure shows the light rays from different views. By using the 3D rendering process, image contents (left-blue, right-red) are assigned to each curve and merged results in the bottom figure is seen to the viewer's eye.

There are various sources of 3D crosstalk such as diffraction or scattering caused by attaching optic elements such as parallax barrier, glue, and color filter in subpixel and refraction and spreading of light rays through the lenticular lens or parallax barrier from subpixels, which is related to the

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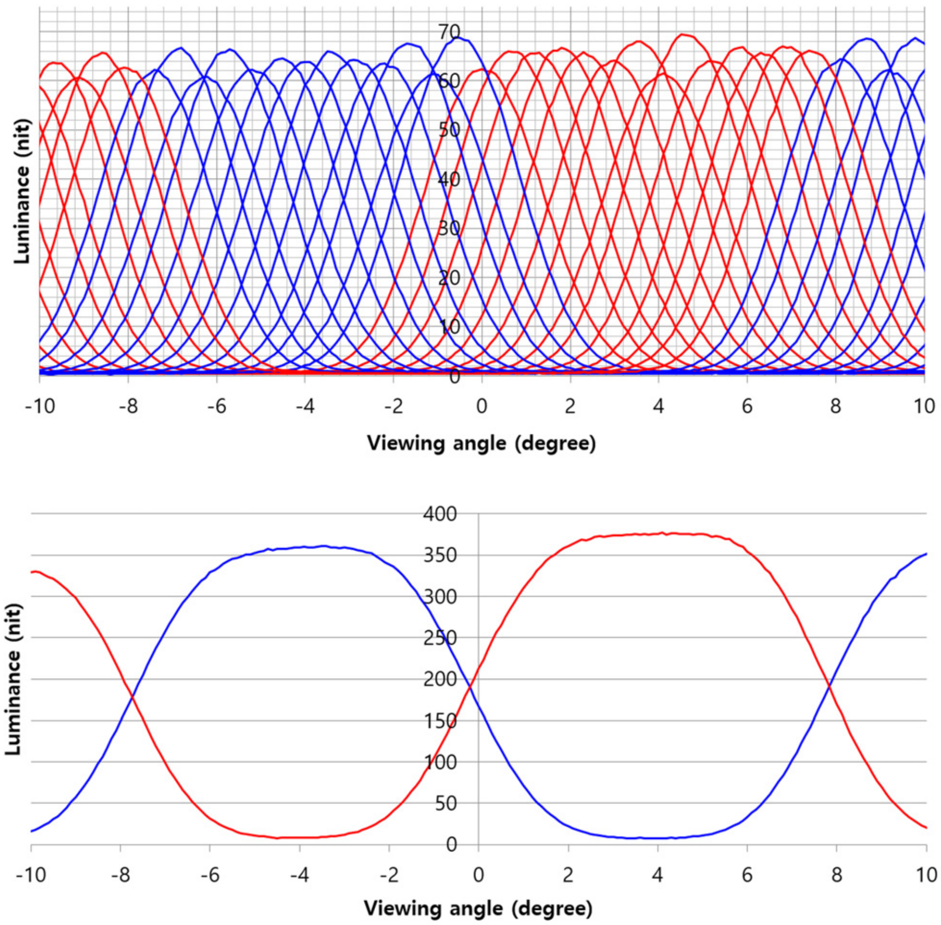


Figure 1. *Merged luminance profile for eye-tracking-based 3D display.*

shape of luminance profile of light ray and this is affected by 3D optics design parameter such as slit size, lens pitch, and slanted angle, and also affected by fabrication errors such as non-uniform gap between panel and parallax barrier and lens aberration. In the IEC (International Electrotechnical Commission) document [11], two concepts of 3D crosstalk are defined: 3D pixel crosstalk from the combination of distributed light rays, and offset crosstalk for diffraction of light source from display optical elements. Figure 2 shows an example of measured crosstalk varying the viewing angle in horizontal direction for fixed eye position. The offset crosstalk can be considered as the minimum baseline which can be seen independently of the viewer's position and 3D rendering process, and 3D pixel crosstalk will increase as the viewer's eye is moved from the optimal position of minimum crosstalk.

3. PROPOSED CROSSTALK REDUCTION METHOD

In our approach, we treated 3D pixel crosstalk and offset crosstalk separately and applied different crosstalk reduction methods considering each characteristic.

3.1 *3D Pixel Crosstalk Reduction*

3D pixel crosstalk is the result of a combined luminance profile at eye position and this combination is determined by the 3D rendering process. Previously authors proposed directional subpixel rendering (DST) method for eye-tracking-based 3D display in [12], and we describe the proposed crosstalk reduction method based on this 3D rendering method.

In DSR, each subpixel value in whole display panel is determined whether it is left or right contents by tracing the ray directions to the viewer's eyes and the nearest barrier opening (or lenticular lens) center from each subpixel and comparing the distances from the projected eye positions to the barrier opening. Because we know how close is the generated light ray to the selected eye, we can apply blending weight according to the distance. The weight increases as light ray becomes close to an eye direction and decreases as it moves further away. It has minimum weight if the light ray passes through the middle of the left and right eyes.

Figure 3 depicts the proposed weighting method using an example of 10 view display. We can think of 10 light rays which are generated from subpixels under a unit barrier opening, and half of them are close to the left eye (v1 ∼ v5) and the others (v6 ∼ v10) are close to the right eye. Because the luminance of light rays becomes maximum when its direction is the closest to eye direction, each luminance component of 10 light rays can be represented like thin

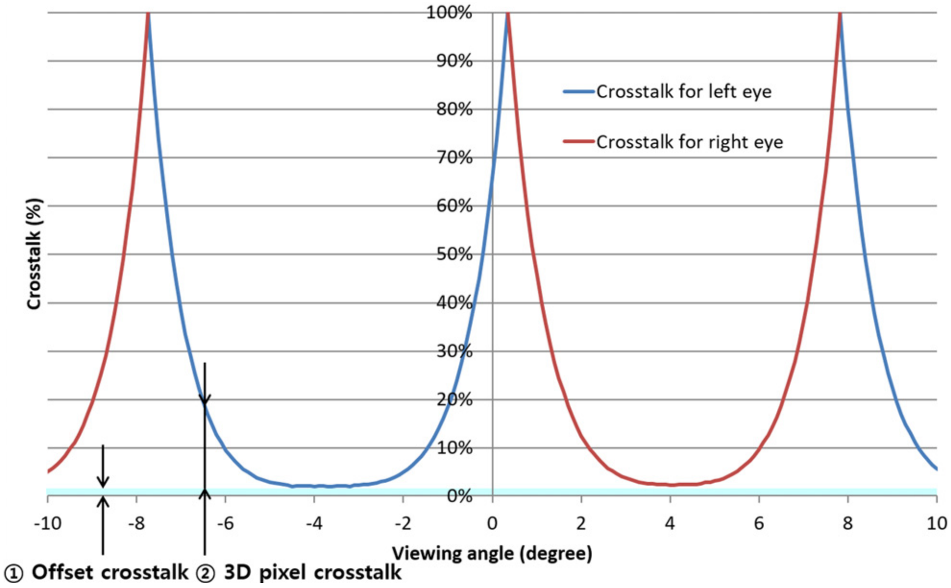


Figure 2. 3D crosstalk along the viewing angle.

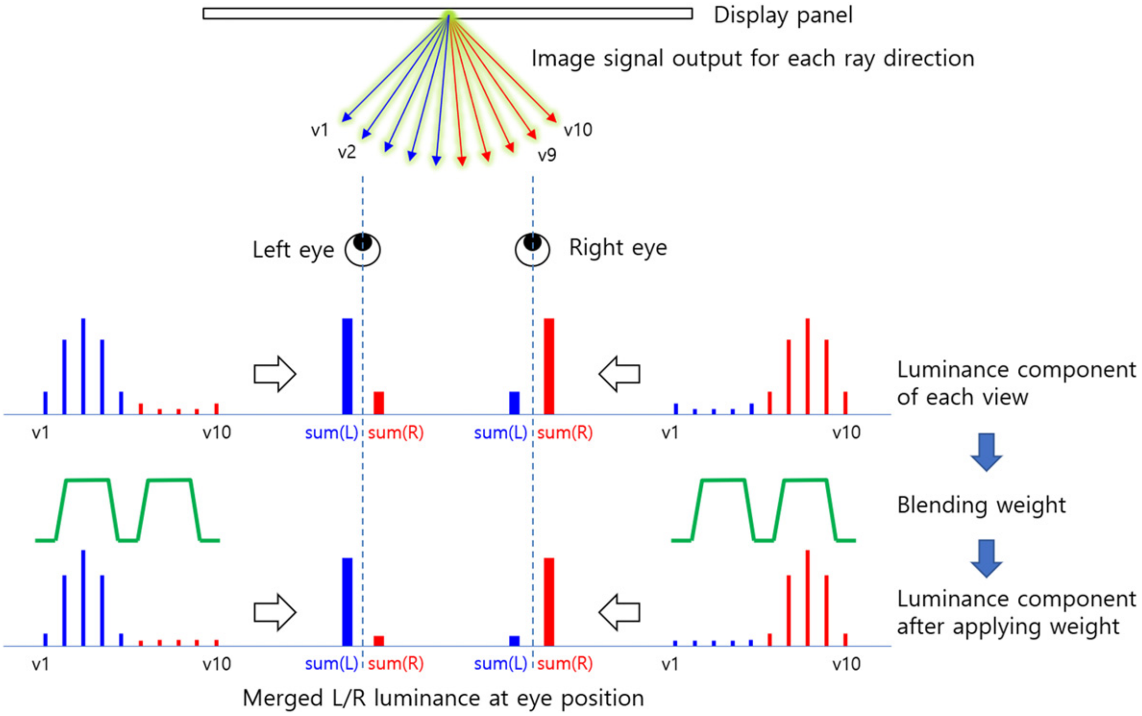


Figure 3. Weighting method for 3D pixel crosstalk reduction.

columns in the middle of Fig. 3 at each eye direction, where blue means left image and red means right image. At the eye position, the merged luminance of each component (thick column) can be seen by the viewer's eyes. After applying the blending weight, the luminance component of light ray which is far from the eye direction will decrease as in the bottom of the figure (red columns in left eye, blue columns in right eye) and the amount of unwanted luminance leakage will be reduced as a result.

3.2 *Offset Crosstalk Reduction*

For offset crosstalk which is evenly distributed for viewing range and independent of viewer's position, we applied a subtractive crosstalk cancelation method. We subtracted luminance of crosstalk components according to the display crosstalk level which is measured in advance. Figure 4 shows offset crosstalk reduction process. We subtract offset crosstalk components for each other from input stereo content, then this crosstalk subtracted content is used for 3D

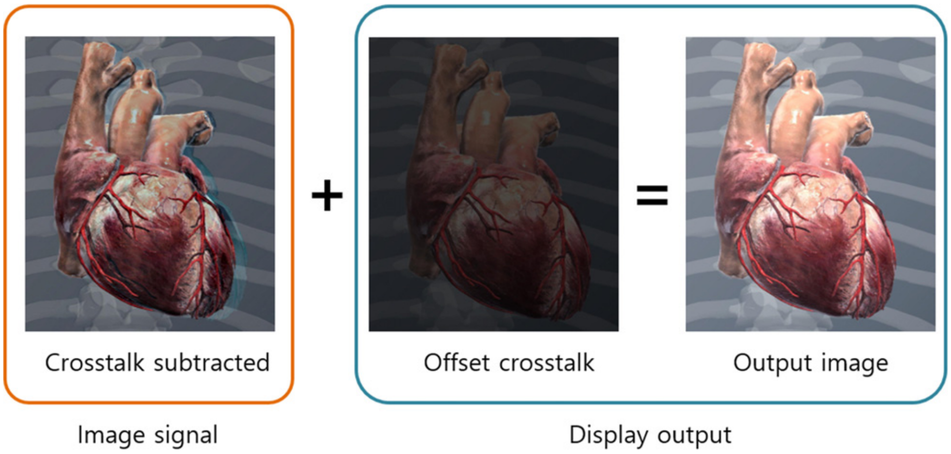


Figure 4. Crosstalk subtraction for offset crosstalk.

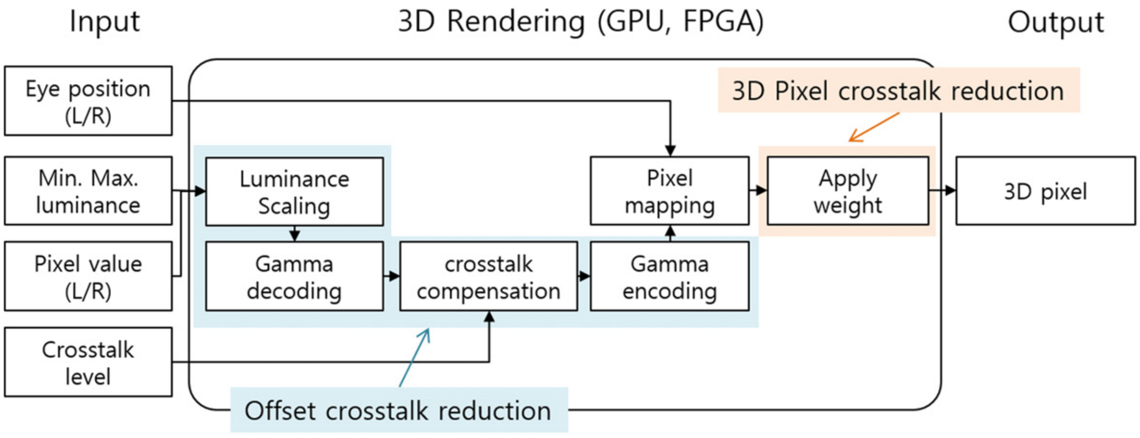


Figure 5. Flow chart of proposed 3D rendering method with 3D crosstalk reduction.

rendering. When a 3D display outputs the resulting image signal, offset crosstalk is added to the output signal and the viewer can see original input content with smaller offset crosstalk.

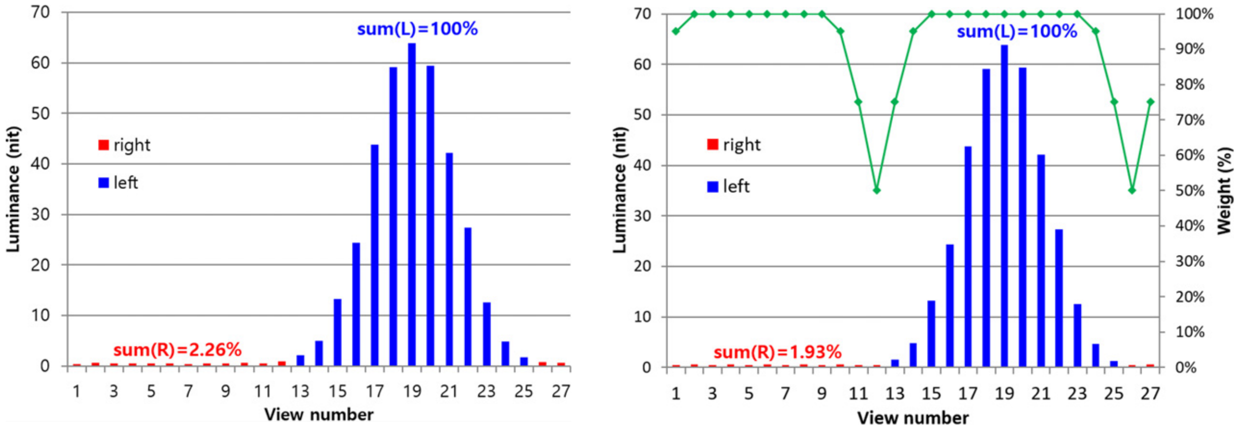
3.3 *Integration of Proposed Crosstalk Reduction Method with 3D Rendering*

Proposed crosstalk reduction method can be integrated to our 3D rendering process in parallel architecture such as GPU and FPGA. Figure 5 shows the overall flowchart of our 3D rendering method. In offset crosstalk reduction, we do not analyze input image to obtain maximum and minimum luminance information for luminance scaling of input image contents and we use predefined static maximum and minimum luminance value for parallel processing of each subpixel rendering. 3D pixel crosstalk reduction is applied after left/right pixel mapping using the distance information between light ray from current subpixel and viewer's eye.

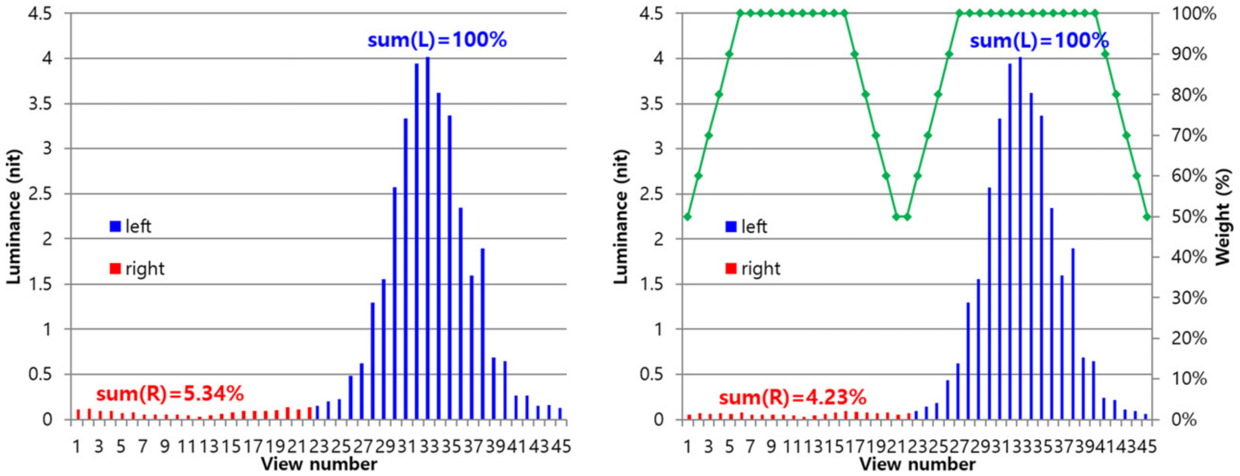
4. EXPERIMENTAL RESULTS

In this section, we present simulation and experimental results for the proposed method. We used our own 3D display prototypes, 10.1" 3D tablet, 31.5" 3D monitor, which is described in [12] in more detail.

Figure 6 shows simulation results for 3D pixel crosstalk reduction at the left eye position. We measured luminance profiles of two prototypes varying the viewing angle and luminance component of each view is plotted (blue columns are mapped to the left eye, red columns are mapped to the right eye). We displayed white image in a view of which luminance component is to be measured, and displayed black image in other views. By applying proposed 3D pixel crosstalk reduction method, the luminance components at boundary view where output contents change from left to right or vice versa is decreased, and the resulting crosstalk is reduced to 1.93% from 2.26% for 3D tablet, and 4.23% from 5.34% for 3D monitor. Table I presents the crosstalk measurements over different viewing angles from −20° to 20° with 5° interval, and results show that the average crosstalk is reduced to 1.93% from 2.28% for 3D tablet, and 4.86% from 5.83% for 3D monitor with standard deviation of 0.08%, 0.28%, respectively. Also, we measured total luminance for each case and it is slightly decreased to 99.6% for 3D tablet and 97.9% for 3D monitor, which means



(a) 10.1” 3D tablet



(b) 31.5” 3D monitor

Figure 6. Comparison of luminance components at left eye position after applying proposed method.

Table I. Simulation result for 3D pixel crosstalk reduction.

	10.1″ 3D tablet			31.5″ 3D monitor		
Viewing angle (degree)	Crosstalk (before)	Crosstalk (after)	Luminance ratio	Crosstalk (before)	Crosstalk (after)	Luminance ratio
−20	2.20%	1.92%	99.7%	6.54%	5.45%	98.1%
−15	2.13%	1.81%	99.7%	5.22%	4.42%	96.3%
−10	2.16%	1.83%	99.6%	5.79%	4.84%	98.0%
−5	2.33%	1.96%	99.6%	5.68%	4.69%	98.2%
0	2.35%	1.97%	99.6%	6.05%	5.05%	98.3%
5	2.37%	1.98%	99.5%	5.70%	4.71%	98.2%
10	2.26%	1.90%	99.7%	5.63%	4.72%	98.1%
15	2.30%	1.94%	99.6%	5.80%	4.79%	98.2%
20	2.45%	2.08%	99.6%	6.06%	5.07%	97.8%
Average	2.28%	1.93%	99.6%	5.83%	4.86%	97.9%
Stdev.	0.10%	0.08%	0.06%	0.34%	0.28%	0.58%

that the luminance is almost maintained after applying the proposed crosstalk reduction method.

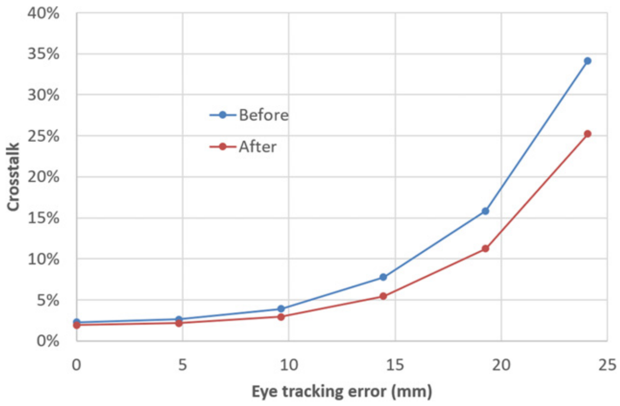
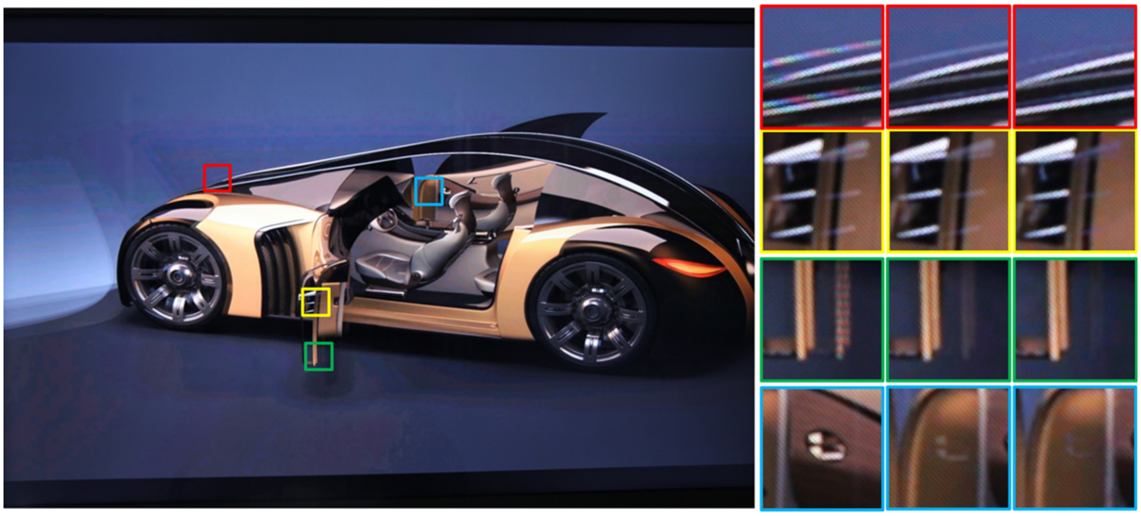
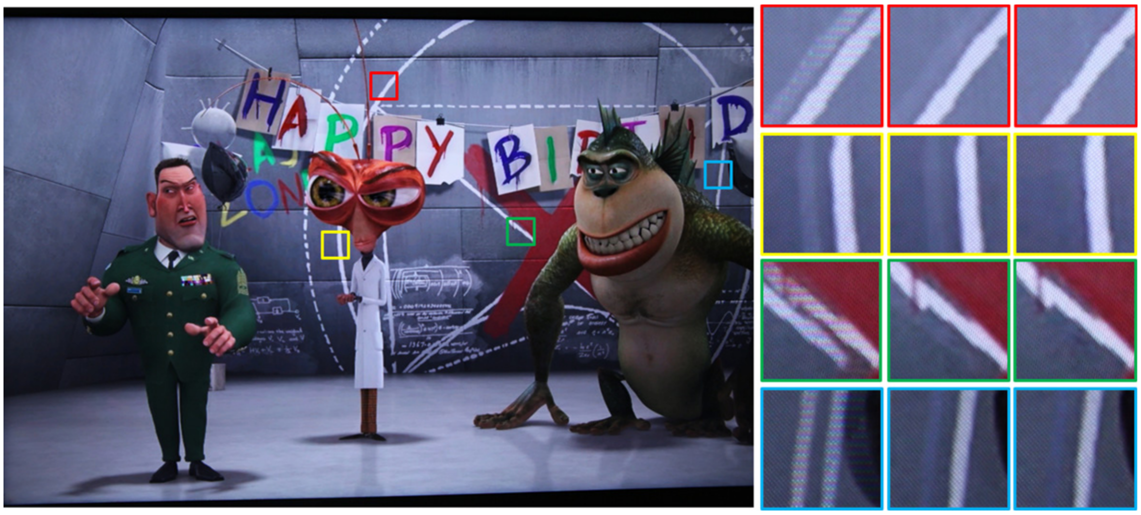


Figure 7. Crosstalk reduction results varying the eye-tracking error.

Figure 7 is the crosstalk simulation result of 10.1” 3D tablet varying eye-tracking error at the left eye position. Eye-tracking results always contain some error caused by tracking algorithm or system latency when the viewer is moving. We can see that 3D pixel crosstalk increases when eye position error from the real eye position increases as described in Section 2. We also found that the proposed



(a) Car



(b) Monster

Figure 8. Comparison of 3D image quality after proposed crosstalk reduction (cropped result: left-without eye tracking, center-before, right-after).

method is effective when eye-tracking error increases. After applying 3D pixel crosstalk reduction, the crosstalk decreased from 2.26% to 1.93% (−0.34%) at 0 mm position error, and from 34.14% to 25.21% (−8.94%) at 24.1 mm position error.

Figure 8 shows some examples for subjective image quality improvement after applying our crosstalk reduction method. The 31.5” 3D monitor prototype is captured by the same camera at the left eye position varying the 3D rendering algorithms. In this experiment, we did not scale the luminance of input stereo contents to prevent distortion of the contrast of the resulting images. In each enlarged bounding box region in (a) car, (b) monster, the crosstalk component which mostly can be seen as double image around edge boundary region of high contrast can be observed in result without eye tracking (left), and we can see decrease of crosstalk component after applying proposed method (right) compared to result by previous method (center).

Table II. Comparison of objective image quality measurement.

	Car		Monster	
	PSNR (dB)	SSIM	PSNR (dB)	SSIM
w/o eye tracking	21.76	0.8680	20.50	0.8195
Before	24.52	0.8859	24.04	0.8819
After	25.01	0.8899	24.31	0.8904

In order to quantitatively compare image quality of the proposed method, we measured PSNR and SSIM for captured images in Fig. 8 with reference images of captured display output of single view contents at the same camera position. The result in Table II shows that objective image quality is also improved after applying the proposed crosstalk reduction method.

5. CONCLUSION

A new crosstalk reduction method for eye-tracking-based 3D display is presented. We applied different approaches considering the characteristics of 3D crosstalk during eye-tracking and 3D rendering process. Experimental results using 3D display prototypes show that 3D crosstalk can be further eliminated and we achieved crosstalk of 1.93% for 3D tablet and 4.86% for 3D monitor with standard deviation of 0.08%, 0.28%, respectively. By comparing display output of 3D images, we found that subjective image quality increased after applying the proposed method by removing the ghost artifacts around object edges. The effect of proposed crosstalk reduction method in 3D perception needs further researches including the vergence-accommodation conflict considering the depth range of 3D contents and observation time in the controlled environment. However, the dizziness was reduced in our intuition when we see the 3D contents with large change of depth.

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