Multi-Zone Digital Crosstalk Reduction by Image Processing in 3D Display

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***Abstract*—The crosstalk is always an issue for 3D displays. In this paper, we proposed a digital image processing method that could further reduce the optical crosstalk in 3D displays. Unlike the previous method, the proposed method—multi-zone digital crosstalk reduction method (MZ-DCR)—is not only based on the software approach, but also on the pixel structure of the 3D displays. In this paper, a patterned retarder 3D display with 2D1G panel was used to demonstrate the improvement of MZ-DCR method. a head tracking system was implemented to further enlarge the viewing angle.**

***Index Terms*—Crosstalk suppression, image processing, patterned retarder 3D display, 3D display.**

I. Introduction

THREE-DIMENSIONAL (3D) system is on the verge of constant development in scientific as well as the entertainment community in recent years. With the progress of the times, the needs of a better 3D vision has been steadily increasing. The 3D system, including stereoscopic and auto-stereoscopic 3D system [1]–[11], can provide 3D images on a flat panel. According to the method of 3D perception in commercial 3D technology, the most common method is to use binocular parallax [12]. Nevertheless, the crosstalk issues in 3D technologies still needs to be further addressed [13]–[19]. The images with crosstalk will substantially lower the image quality, and cause an uncomfortable feeling. Moreover, the ghost image will even disable the ability of the human brain to fuse the two images together. For these reasons, decreasing the crosstalk in 3D systems is an essential and highly expected task. There are several methods have been proposed to reduce crosstalk [20], [21], but the low brightness and extra devices are still unsolved problems in these methods. Therefore, some of the researchers proposed the software approach to address the crosstalk issue.

To our best knowledge, the first one who used the image processing approach to reduce crosstalk can be traced back to the work by Lipscomb *et al.* [22] in 1994. Their Anti-crosstalk processing can effectively reduce the crosstalk but perhaps limited to some artificial representations.

HyungKi Hong modify the 3D image data depends on the display positions of the shutter glasses 3D display to reduce the light leakage [23]. Reduction the 3D crosstalk were determined at the vertical nine positions on the 3D display. When modification conditions were interpolated from these determined conditions, ghost artifact was observed to decrease for all the positions of 3D display.

Chang *et al.* proposed the Digital Crosstalk Reduction [24] method to suppress crosstalk without any extra devices. After applying their method, the crosstalk of two-view display has been proved to be less than 5%, and the crosstalk of 32-inch 12-view display was reduced from 53.2% to 9.6% at the best viewing angle. Furthermore, this approach can be applied to any 3D display systems using binocular parallax method.

Although the methods discussed above can successfully suppress the crosstalk without adding any extra device or varying the structure of display in almost every 3D displays, the potential of image processing approach have not yet been fully discovered. Therefore, we proposed a Multi-Zone Digital Crosstalk Reduction (MZ-DCR) method to further reduce the crosstalk in 3D display.

II. Multi-Zone Digital Crosstalk Reduction (MZ-DCR) Method

The MZ-DCR method controls the image signal based on the structure of a 3D display system to counteract the light leakage. In order to make it more comprehensible, in this paper, we will take the patterned retarder 3D display as an example. Furthermore, the MZ-DCR method can also be applied to the auto-stereoscopic display, for example, lenticular lens type 3D display or barrier type 3D display.

To apply the MZ-DCR method to the patterned retarder 3D display, an individual zone controllable panel is required. The pixel layout of this multi-zone panel is shown in Fig. 2, compared with a regular panel. The number of zones of this particular panel is not restricted. In this paper, a 2D1G panel (with two zones) is used [25], [26] which divided the original sub-pixel of regular panel into main and sub regions. With its two data lines and one gate line architecture, the main and sub regions can be controlled individually.

The inherent drawback of the patterned retarder display is depicted in Fig. 1. The crosstalk of this kind of display is mainly caused when watching the panel in large viewing angle, and is extremely sensitive to the vertical viewing angle. In some cases, even a slight movement of the user's head will largely affect the 3D image quality. The observer might receive part

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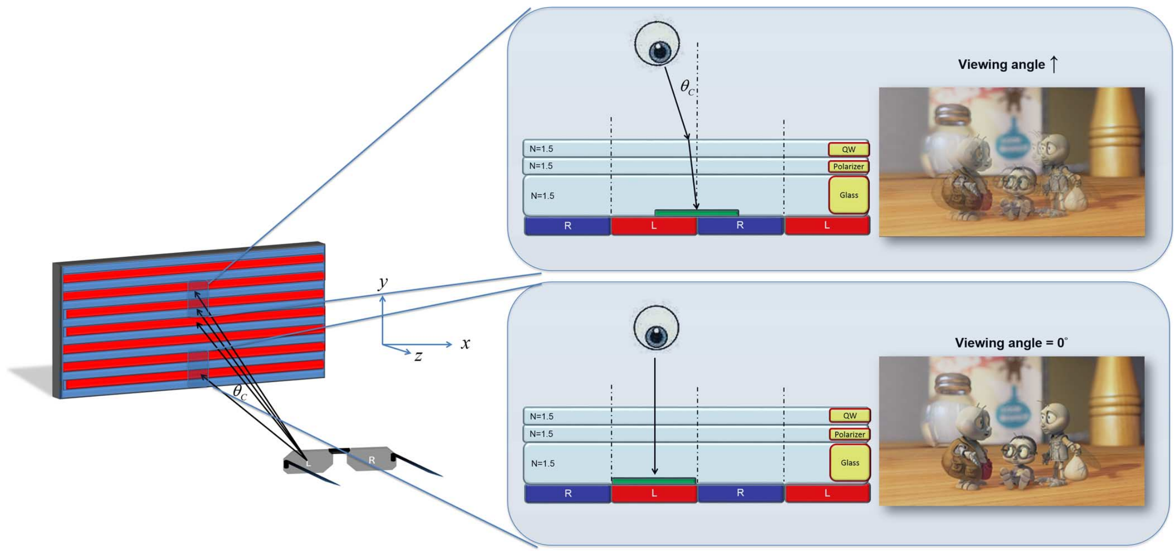


Fig. 1. User watches a patterned retarder display in vertical direction. The images at the right side show main components of the pattern retarder display and the corresponding images at different viewing angle.

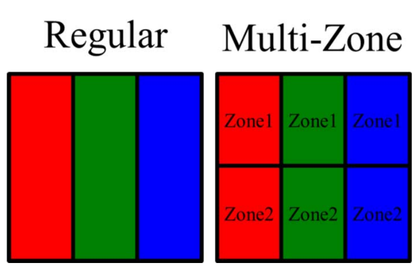


Fig. 2. Comparison of pixel layout of a regular panel and a 2D1G panel.

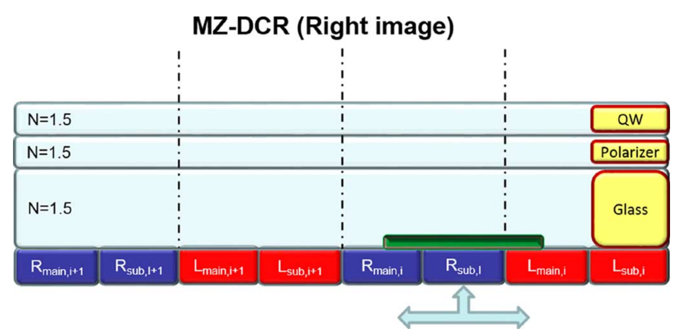


Fig. 3. Principle of MZ-DCR method in right image.

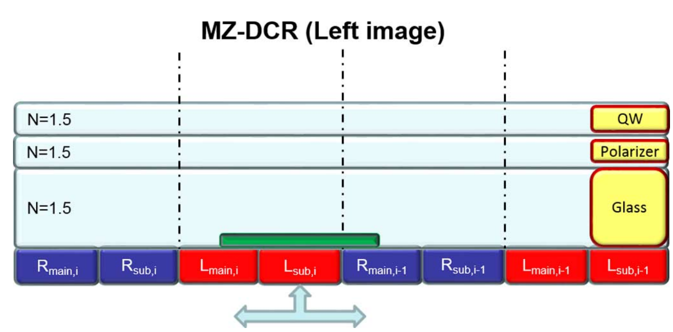


Fig. 4. Principle of MZ-DCR method in left image.

of light leakage which belongs to the other eye. When the user watches the 3D display in large vertical viewing angle, the light leakage will become larger and so does the crosstalk. At the right side of Fig. 1, the green region represents the area that the user perceived, and it will shift as the user deviates away from the previous viewing angle. From these figures, one can easily find out where the crosstalk comes from.

A. Principle of MZ-DCR Method

The light leakage that comes from another view is the main reason causing the high crosstalk. Our goal is to counteract the optical crosstalk by modifying the output gray level of each pixel. The principle of MZ-DCR method for right and left image were depicted in Figs. 3 and 4. The main purpose of the MZ-DCR method is—when watching the panel in large viewing angle, even the viewing area is slightly changed, the image that observer receives will remain the same. Hence, the gray level of main region should be similar with both R and L images. The modification process is as follows.

First of all, (1) and (2) each represent the output signal of $R_{\mathrm{main,i}}$ and $L_{\mathrm{main,i}}$. In the (1), $\mathrm{GL}_{\mathrm{R,i}}$ and $\mathrm{GL}_{\mathrm{L,i+1}}$ are the original gray level of R_{i} and $L_{\mathrm{i+1}}$ pixel, both of which are the pixels next to the $R_{\mathrm{main,i}}$; in the (2), $\mathrm{GL}_{\mathrm{R,i}}$ and $\mathrm{GL}_{\mathrm{L,i}}$ each represent the original gray level of R_{i} and L_{i} pixel which are adjacent to the $L_{\mathrm{main,i}}$.

To decide which calculation in (1) and (2) should be used for $R_{\mathrm{main,i}}$ and $L_{\mathrm{main,i}}$, we first estimate whether the original gray level can be compensated for, if we replace the gray level of common (shared) area into the minimum of the adjacent pixels. The judgments that determine which calculation should be used for $R_{\mathrm{main,i}}$ and $L_{\mathrm{main,i}}$ are shown in (3) and (4).

If the calculated result is less than or equal to zero, it means that the original gray level can be replaced and further divided into two parts. Therefore, we modify the $R_{\mathrm{main,i}}$ as the same part of R_{i} and $L_{\mathrm{i+1}}$ $(\min(R_i, L_{i+1}))$, and the $L_{\mathrm{main,i}}$ as the same part of R_{i} and L_{i} $(\min(R_i, L_i))$; otherwise, we change the gray level as the average of both its adjacent pixels ($\frac{R_i+L_{i+1}}{2}$ for $R_{\mathrm{main,i}}$ and $\frac{R_i+L_i}{2}$ for $L_{\mathrm{main,i}}$). The main purpose of changing the gray level as the average of both adjacent pixels is, when the brightness of main region cannot make up the deficiency of the original one $(judge > 0)$, the gray level of main region should become brighter.

$$R_{\mathrm{main,i}} = \left\{ \begin{array}{ll} min(GL_{R,i}, GL_{L,i+1}), & judge \le 0 \\ \dfrac{GL_{R,i} + GL_{L,i+1}}{2}, & judge > 0 \end{array} \right\} \quad (1)$$

$$L_{\mathrm{main,i}} = \left\{ \begin{array}{ll} min(GL_{R,i}, GL_{L,i}), & judge \le 0 \\ \dfrac{GL_{R,i} + GL_{L,i}}{2}, & judge > 0 \end{array} \right\} \quad (2)$$

$$\begin{aligned} judge_{R,i} = {} & \frac{GL_{R,i}}{255} - \frac{\min(GL_{R,i}, GL_{L,i+1})}{255} \times \frac{A_{\mathrm{main,i}}}{2A} \\ & - \frac{\min(GL_{R,i}, GL_{L,i})}{255} \times \frac{A_{\mathrm{main,i}}}{2A} \end{aligned} \quad (3)$$

$$\begin{aligned} judge_{L,i} = {} & \frac{GL_{L,i}}{255} - \frac{\min(GL_{R,i}, GL_{L,i})}{255} \times \frac{A_{\mathrm{main,i}}}{2A} \\ & - \frac{\min(GL_{R,i-1}, GL_{L,i})}{255} \times \frac{A_{\mathrm{main,i}}}{2A} \end{aligned} \quad (4)$$

where

i = the number of pixel in vertical direction;

$GL_{R,i},\ GL_{L,i}$ = the gray level of pixel i in R and L image;

$A, A_{\mathrm{main,i}},\ A_{sub,i}$ = the area of total main and sub region;

$$R_{sub,i} = \left(GL_{R,i} - R_{\mathrm{main,i}} \times \frac{A_{\mathrm{main,i}}}{A} \right) \times \frac{A}{A_{sub}} \quad (5)$$

where $R_{\mathrm{main,i}}, R_{sub,i}$ is the output gray level of main and sub region of the right image, and

$$L_{sub,i} = \left(GL_{L,i} - L_{\mathrm{main,i}} \times \frac{A_{\mathrm{main,i}}}{A} \right) \times \frac{A}{A_{sub}} \quad (6)$$

where $L_{\mathrm{main,i}}, L_{sub,i}$ is the gray level of main and sub region of the left image.

Once the $R_{\mathrm{main,i}}$ and $L_{\mathrm{main,i}}$ were determined, the output gray level of $R_{\mathrm{sub,i}}$ and $L_{\mathrm{sub,i}}$ can be obtained by (5) and (6) to compensate for the original gray level. Consequently, the MZ-DCR method can maintain the original gray level of the image content, which counteract the optical crosstalk successfully.

III. Experimental Results

In order to evaluate the improvement of the MZ-DCR method in patterned retarder 3D display, several simulated images of the MZ-DCR method were compared with the original image as shown in Fig. 5. These images were simulated by a simulation platform which was presented recently [27]. This platform can simulate the light profile and optical crosstalk on the patterned retarder 3D display and show the perceived image of the user.

In Fig. 5, a 2D1G patterned retarder 3D display was simulated, and the area ratio of the sub region to main region is 2 to 1. The original image at the left side of Fig. 5 means that the main region of the 2D1G panel is turned on. It is easy to perceive the difference between these two pictures, especially in the red circles. The light leakage in the image with MZ-DCR method is the same as the original one, yet the ghost phenomenon have been dramatically eliminated.

Fig. 5. Comparison of original image and image with MZ-DCR method.

Please note that, in the comparison, we did not use any instrument to measure the light profile. It is mainly because that the MZ-DCR method is armed to counteract the optical crosstalk, which means we cannot define how much crosstalk was improved and counteracted by measuring the light profile or intensity.

As stated before, the idea of MZ-DCR method is to counteract the light leakage, but how much crosstalk could MZ-DCR method reduce? Actually, it depends on the gray level of each pixel, which means that the compensation ability of MZ-DCR method will vary as the output image changes. In here, we consider the worst case to demonstrate the limitation of MZ-DCR method. With a different area ratio between main region and sub region, the maximum angle, MZ-DCR method can completely counteract the crosstalk, is changed as depicted in Fig. 6. The areas in blue color indicate the maximum gray level that

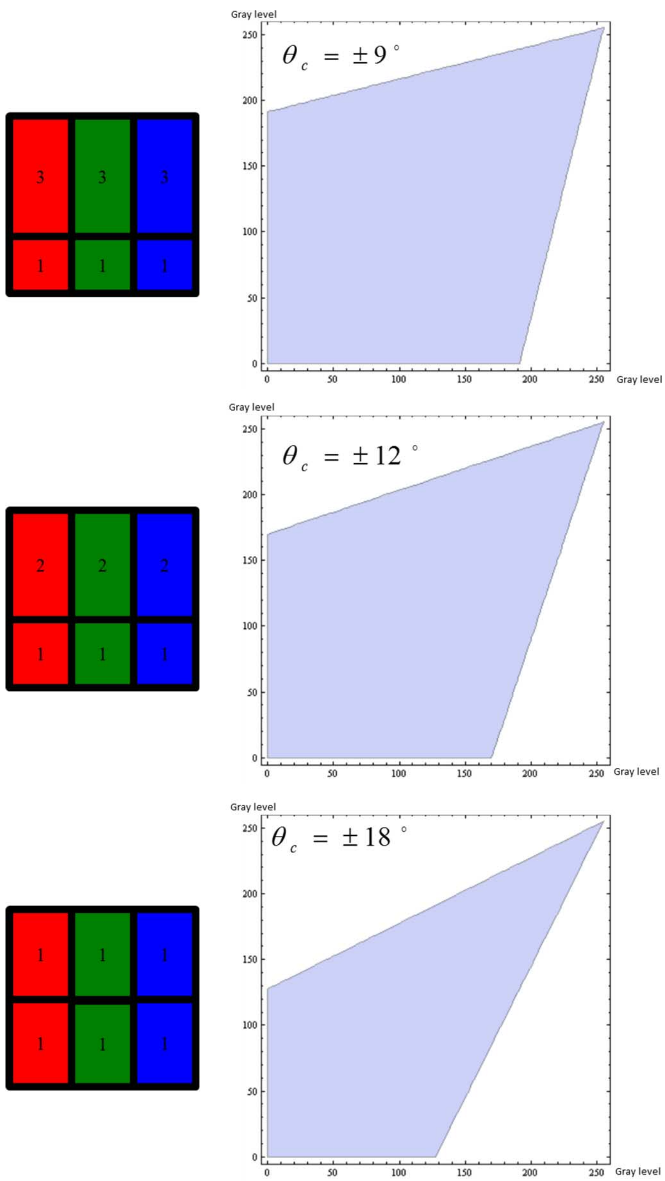


Fig. 6. Limitation of MZ-DCR method corresponding to the gray level of each pixel and the ratio between main region and sub region. The θ_c indicates the maximum angle that MZ-DCR method can counteract the crosstalk.

the MZ-DCR method can successfully counteract in different viewing angle (θ_c). From Fig. 6, we can find out the θ_c will decrease as the ratio of the sub region and main region become higher, and the usable gray level would be extended instead. Thus, we should appropriately adapt the suitable ratio of the main and sub pixels for different viewing conditions and scenarios. For example, when watching a 65-inch 3D display at a distance about 3 m, the ratio of 3 to 1 is sufficient for the user to perceive perfect 3D vision. However, if the viewing distance is close to 2 m, the ratio needs to be changed to 2 to 1.

Another comparison is demonstrated in Table I which contains the results of original, DCR method and MZ-DCR method in different viewing angles. The image in the original design will be damaged when the viewing angle increased as stated before. By applying the DCR method, the crosstalk can be reduced in almost every viewing angle, but the over-reduced artifact at 0° and crosstalk phenomenon at large view angle can still interfere the user to fuse stereo images. On the contrary, the proposed MZ-DCR method can successfully eliminate the crosstalk at the normal viewing condition. It not only completely removes the ghost phenomenon, but also maintains the luminance of the 3D images when compared with DCR method. By applying the MZ-DCR method, generally, the viewing angle can be extended to 15 degree. However, the maximum extendable viewing angle of our proposed method actually varies in different images. It is highly related to the gray level of the original image as demonstrated in Fig. 6.

In order to know how much the quality have been improved, we thus used the structural similarity (SSIM) index to measure the quality of the output image. The SSIM index measures the image quality based on an initial uncompressed or distortion-free image as reference, and it has been proven to be consistent with the human eye perception [28]. The higher score indicates that the output image is similar to the reference (original) image. We took the original image at 0 degrees as reference, and showed the SSIM score under each test image. From these scores, the proposed SDCR method has been proven to improve the image quality in every viewing angle. It also demonstrated that the output image maintained a 0.99 scores at 15 degrees, while the original image only obtained a 0.97 scores.

IV. MZ-DCR Method With Head-Tracking System

The proposed method is aimed to counteract the light leakage in 3D display. The experiment results have demonstrated that under the normal viewing condition, the MZ-DCR method can further improve the image quality. However, as the viewing angle constantly increased as the user moves toward the display, the perceived area (green region in Figs. 3 and 4) will eventually exceed the range of the original pixel. Consequently, the viewing angle of the proposed MZ-DCR method with two zone controllable panel is still somewhat limited.

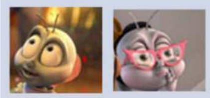
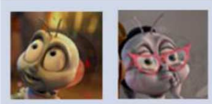
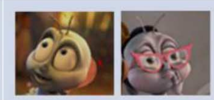
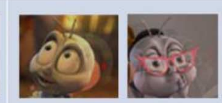
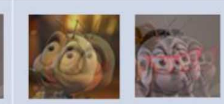
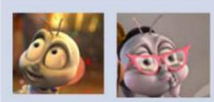
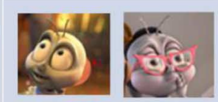
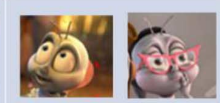
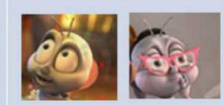
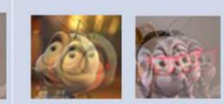
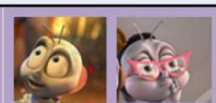
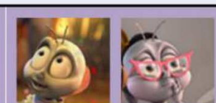
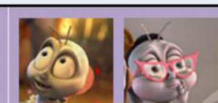
Under this condition, in order to provide the 3D image in almost all viewing zones, our system should "shift" the output signal to the neighbor pixel according to the viewing angle. Thus, a head tracking system is required. Furthermore, in order to satisfy the circumstance that we can always use the small region to counteract the light leakage where ever the user moves, a panel with 3 controllable sub regions is favorable. The simulated results of MZ-DCR method with the head tacking system on a panel with three-zones are shown in Table I, which indicates that with the tracking devices, the ghost phenomenon at a large viewing angle can be still counteracted.

V. Discussion

For the multi-view auto-stereoscopic 3D display, the different views in the horizontal direction will result the same impact as multi-zone sub-pixels on patterned retarder 3D display. With more numbers of sub-pixels or views, the MZ-DCR method could counteract the optical crosstalk completely and generate intact 3D images for the user. Thus, the MZ-DCR method should be also useful on auto-stereoscopic 3D display.

The MZ-DCR method (with the same design in this paper) also been implemented on a 32-inch lenticular lens type 3D display with 12 views, and captured the perceived image by a regular color camera. The results are shown in Fig. 7. Although

TABLE I
SIMULATED IMAGE OF MZ-DCR METHOD COMPARE WITH THE ORIGINAL IMAGE AND THE IMAGE AFTER DCR METHOD

Viewing angle	0°		5°		10°		15°		30°	
Original										
MSSIM	1	1	0.9947	0.9955	0.9847	0.9860	0.9700	0.9717	0.9048	0.9067
DCR										
MSSIM	0.9566	0.9600	0.9643	0.9649	0.9616	0.9616	0.9509	0.9509	0.8846	0.8853
MZ-DCR										
MSSIM	0.9916	0.9927	0.9925	0.9937	0.9920	0.9932	0.9890	0.9909	0.9178	0.9210
MZ-DCR with head tracking										
MSSIM	0.9916	0.9927	0.9925	0.9937	0.9920	0.9932	0.9909	0.9921	0.9935	0.9932

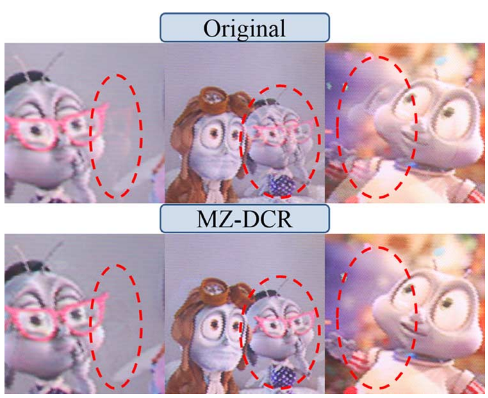


Fig. 7. Experimental result of MZ-DCR method on a 32-inch multi-view lenticular lens type 3D display. Top: the original image captured by color camera. Bottom: the output image of proposed MZ-DCR method captured by color camera.

only partial results are shown in here, these results proved that the MZ-DCR method is also helpful on the multi-view 3D displays. However, at this time, we only adapted the exact same MZ-DCR method elaborated in this paper. This method will reduce the total number of views to one third of the original design. For example, the number of views will be reduced from 12 to 4 in our experiment. Thus, it should be more suitable for multi-view displays with larger number of views. On the other hand, this MZ-DCR method not only provide a software approach to eliminate the ghost phenomenon in multi-view 3D display, but also present an alternative way to adjust the number of views. The method could instead use other schemes (e.g., 2 to 1, or 4 to 1), though not investigated here. Furthermore, we expect an even greater improvement could be obtained by modifying the output gray level of (1) and (2). An alternative would be to replace the average $(\frac{R_i+L_i}{2})$ to the root $(\sqrt{R_i \times L_i})$ of both adjacent pixels.

VI. CONCLUSION

Images containing three-dimensional coordinate information are necessary for humans to perceive real life images. However, no matter in stereoscopic or auto-stereoscopic display, there are always ghost phenomena on the image that will make the observer feel extremely uncomfortable and even unable to fuse the two images together. In order to further improve the crosstalk in large viewing angle, we proposed Multi-Zone Digital Crosstalk Reduction (MZ-DCR) method to remedy and improve the image quality. The MZ-DCR method utilized the structure of a controllable multi-zone panel to counteract the light leakage. From the comparison, the MZ-DCR method has been proven to successfully eliminate the ghost phenomenon under the normal viewing condition and can further extend the viewing angle to 15 degrees while maintaining the luminance. Even at the different viewing angle, the MZ-DCR method is still constantly outperform the original one and DCR method. We also proposed that combing the head-tracking system and three zone controllable panel with the MZ-DCR method can provide the intact image in every viewing angle.

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