A Novel Chromatic Aberration Correction Method for VR Display

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Abstract

The chromatic aberration is an inevitable artifact caused by refractive characteristics of the lens. A novel image processing system was proposed to correct the lateral chromatic aberration in this paper. The experimental results show that the color fringes along image edge are removed and the color shift are avoided.

Author Keywords

Chromatic Aberration; Virtual Reality; Image Processing

1. Introduction

Thanks to the development of micro-displays, chips, and optical lens, the virtual reality (VR) devices have gained great interest in the market. However, the chromatic aberration introduced by optical system has greatly affected the immersion. In this phenomenon, the unnatural color fringes usually occur along edges of an image, which is caused by the refractive characteristics of the lenses as shown in Figure 1.

Figure 1. Unnatural Color Fringes

There are two forms of the chromatic aberration: the lateral aberration and the longitudinal aberration, as shown in Figure 2. The lateral aberration causes the red, green and blue components of a pixel on the panel to be scattered at different location on a virtual image plane. The longitudinal aberration will cause the red, green and blue components of a pixel on the panel to be focused on different virtual image planes. The former causes channel shifts and the latter generates color blur in the photographs. In VR application, the lateral chromatic aberration is the main factor affecting the visual quality.

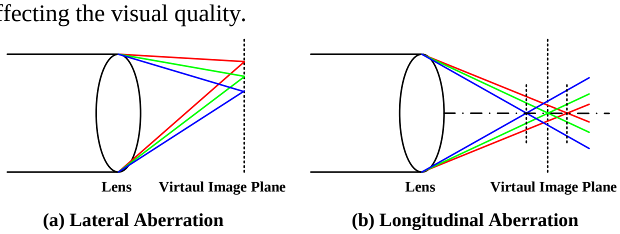

Figure 2. Two Forms of the Aberration

There are two methods of CAC (Chromatic Aberration Correction): optical lens design [1] and digital image processing [2-4]. Optical lens design can compensate the chromatic aberration by using exquisite lenses, which means that these lenses will be very bulky and expensive. An alternative to the optical method is using digital image processing techniques. Existing image processing algorithms are designed for ISP (Image Signal Processor) pipeline of the camera. These methods usually correct the chromatic aberration in RAW domain and could be divided into two stages: distortion computation and warp application [2].

However, the VR display processing is different from ISP. The light source of VR is micro-display and it means that the size of light source is limited. In addition, the image signal has also been encoded to the non-linear domain. So, existing methods cannot be applied to VR directly.

A novel image processing system was proposed in this paper and this system could correct the lateral chromatic aberration in VR application. It is worth noting that both of the above two issues have been solved in this system.

Firstly, the size of panel is limited, and the screen in the FOV (Field Of View) may be masked into a specific shape in VR application. These requirements cause the boundaries of the light source to appear in the FOV. The color fringes will appear along these boundaries and they cannot be solved by channel shifting. To solve the issue, a CEC (Color Edge Compensation) module was designed. It could calculate pixel locations related to the color edge based on the shifting model and control their brightness.

Secondly, since the image signal has been encoded into the non-linear domain, the ordinary pixel generation method will cause the luminance decrease for the specific color channel, which will cause the color shift. So, a luminance compensation method was designed to solve this issue.

In conclusion, there are three contributions in this paper.

- A novel image processing system was proposed to correct the lateral chromatic aberration.
- The issues of color shift and color edge were analyzed and the corresponding solutions were designed.
- The experiments were designed to prove the effectiveness of the system.

2. Theory

2.1. Description of CAC

As shown in Figure 2(a), the lateral chromatic aberration is caused by the different refractive indexes of the lens for R/G/B components. In other words, three different pincushion distortions are applied to R/G/B channel respectively and resulting the color channel shifting.

An intuitive solution is to construct three warp models for R/G/B channel to apply different barrel distortions as shown in Figure 3. Thence, the distortion correction and chromatic aberration correction could be completed at the same time.

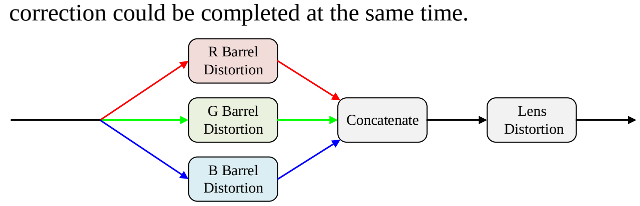

Figure 3. Multi-Channels Barrel Distortion

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However, the R/G/B channels are misaligned after chromatic aberration correction, which will affect some modules that use color channel correlation, such as color correction and sub-pixel rendering. Therefore, a more recommended solution is to separate the distortion correction and chromatic aberration correction as shown in Figure 4.

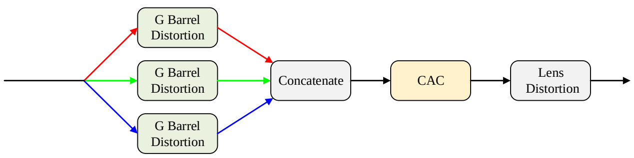

Figure 4. Multi-Modules Processing

2.2. Color Edge Issue

In VR application, the light source is panel, which is different from image signal processor in camera. The limited panel size means that the border of the panel may appear in the field of view. Besides, the active area of the panel may be masked in order to present a specific shape in the FOV.

As shown in Figure 5, take white pattern as an example to analyze this phenomenon. The white pixel observed through the lens (virtual pixel) is composed of R/G/B channels from three different pixels of the panel (real pixel). In the color edge area, the virtual pixel is only composed of one channel or two channels because the real pixels corresponding to the missing channels are outside the active area of the panel.

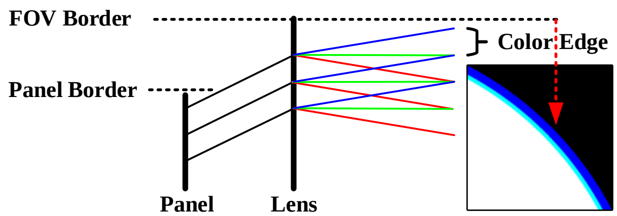

Figure 5. Color Edge Caused by Panel Border

The analysis of color edge caused by mask is the same as the above description as shown in Figure 6.

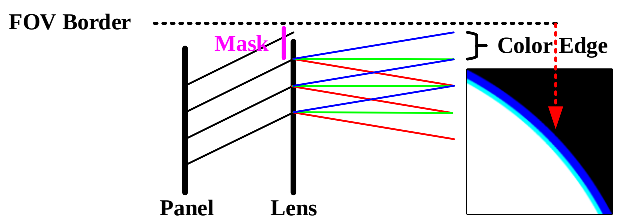

Figure 6. Color Edge Caused by Mask

2.3. Color Shift Issue

The image signals have been encoded by gamma curve, which means that the CAC module has to work in non-linear domain. As shown in Figure 4, since the barrel distortions of all three channels are performed based on the parameters of green channel, the pixel values of red and blue channels need to be generated by interpolation.

However, the interpolation in non-linear domain will cause luminance decrease for red and blue channels. In Figure 7, the luminance of p1 is o1 and the luminance of p2 is o2. The average luminance of p1 and p2 in the non-linear domain is *ea*. The average luminance of p1 and p2 in linear domain is oa. The average operation causes the luminance loss since oa is larger than *ea*.

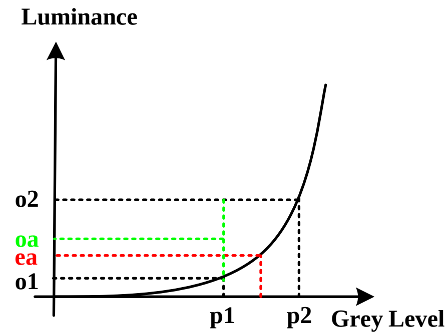

Figure 7. Luminance Decrease

As shown in Figure 8, assume that the pixel values (224/224) of R/B channels are the interpolated results, together with G 255, it will cause the color shift compared with the original white.

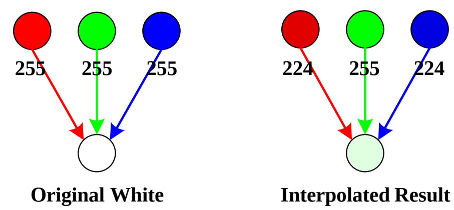

Figure 8. An Example of Color Shift

3. Method

3.1. Overview

In order to correct chromatic aberration in VR application, a novel CAC system including three modules was proposed as shown in Figure 9. *Pre-Calibration* is used to evaluate the degree of aberration and construct a shifting model for the specific lens. *Coordinates Calculation* is used to map the coordinates according to the shifting model. *Pixel Generation* is used to generate new pixel values.

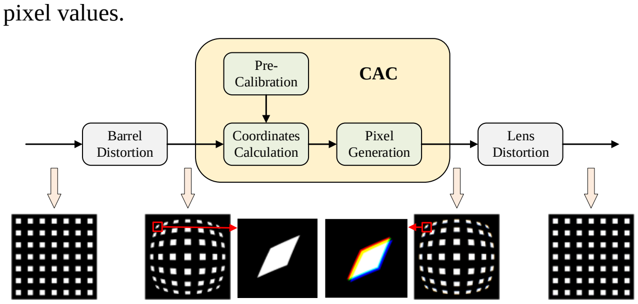

Figure 9. CAC System in VR Application

3.2. Pre-Calibration

In this module, the distortion model needs to be constructed for each color channel. This process can use the same model as the distortion correction to save memory and power.

The model could be divided into three categories: brown-conrady model [5], division model [6] and mesh table.

The brown-conrady could be described as equation (1)-(2).

$$x_d = x_c + (x - x_c)(K_1 r^2 + K_2 r^4 + K_3 r^6 + \cdots) \quad (1)$$

$$y_d = y_c + (y - y_c)(K_1 r^2 + K_2 r^4 + K_3 r^6 + \cdots) \quad (2)$$

The division model could be described as equation (3)-(4).

$$x_d = x_c + (x - x_c)/(1 + K_1 r^2) \quad (3)$$

$$y_d = y_c + (y - y_c)/(1 + K_1 r^2) \quad (4)$$

In where, (x_c, y_c) is the distortion center and r is the Euclidean distance between the distortion center and distorted point.

The mesh table is a recommended model to describe the transformation relationship considering the errors introduced by assembly.

The above models could be fitted by lens parameters or NED camera shooting. An example of calibration patterns is shown in Figure 10.

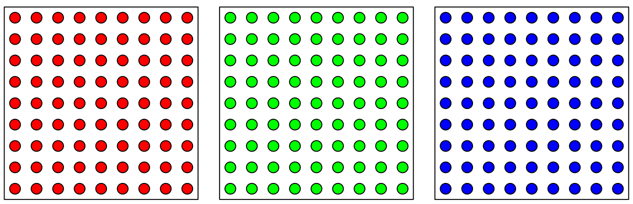

Figure 10. An Example of Calibration Patterns

The transformations of barrel distortion and pincushion distortion can be established. These two processes are represented by equation (5) and (6) for a clear description.

$$p' = BarrelTrans(p, \text{"}color\ channel\text{"}) \quad (5)$$

$$p = PincushionTrans(p', \text{"}color\ channel\text{"}) \quad (6)$$

3.3. Coordinates Calculation

Since barrel distortion is performed based on green channel, coordinates of red and blue channels need to be calculated. There are two steps to complete this process as shown in Figure 11, which is called "shift model" in this paper.

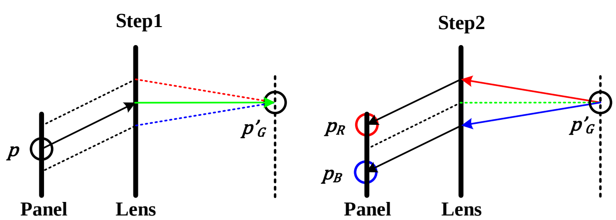

Figure 11. Coordinates Calculation

Firstly, calculate the coordinates of virtual pixel based on green channel.

$$p'_G = PincushionTrans(p, \text{"}G\text{"}) \quad (7)$$

Secondly, calculate the coordinates of R/B channels in the panel.

$$p_R = BarrelTrans(p'_G, \text{"}R\text{"}) \quad (8)$$

$$p_B = BarrelTrans(p'_G, \text{"}B\text{"}) \quad (9)$$

In addition, the shift model could be described by mesh table or formulation [7].

3.4. Pixel Generation

There are two steps in this module: color edge compensation and pixel interpolation.

Firstly, the processing of color edge compensation is similar to coordinates calculation mentioned in section 3.3, except it is based on the red channel. In Figure 12, the last white virtual pixel is composed of p1-R, p2-G, and p3-B. So, the p1-G, p1-B and p2-B causes the color edge. Therefore, a simple solution is to turn off p1-G, p1-B and p2-B.

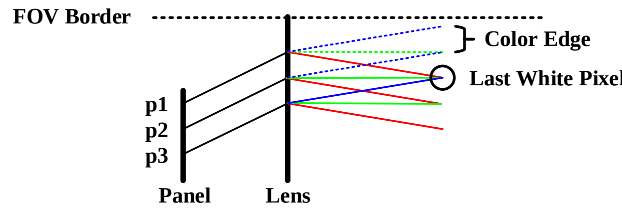

Figure 12. Color Edge Compensation

The location of p1 is the border of panel or mask, and the locations of p2 and p3 could be calculated as following equations.

$$p'_1 = PincushionTrans(p_1, \text{"}R\text{"}) \quad (10)$$

$$p_2 = BarrelTrans(p'_1, \text{"}G\text{"}) \quad (11)$$

$$p_3 = BarrelTrans(p'_1, \text{"}B\text{"}) \quad (12)$$

Secondly, the pixel interpolation could use bi-cubic [8], bi-linear and others.

$$g = Interp(g_1, g_2, g_3, g_4) \quad (13)$$

As mentioned in section 2.3, a simple solution is to convert the grey level to linear domain by gamma.

$$g_o = Interp(g_1^\gamma, g_2^\gamma, g_3^\gamma, g_4^\gamma) \quad (14)$$

$$g = g_o^{\frac{1}{\gamma}} \quad (15)$$

In where, g is the pixel value and γ is the EOTF parameter.

In addition, the low-pass filter can be applied during the interpolation to reduce aliasing.

4. Result

The image processing pipeline is shown in Figure 4 and lens distortion is an optical phenomenon in VR application. Therefore, the result of lens distortion cannot be presented intuitively. In this section, the lens distortion is simulated by pincushion transformation using image processing.

Table 1. Compared Method

Method	Barrel Distortion	CAC	Lens Distortion
Proposed Method	Based G	enable	enable
No Process	Based G	disable	enable
Multi-Channels	R/G/B	disable	enable
Input	disable	disable	disable

In order to show the performance of the proposed system, other three solutions will be as the comparison. The multi-channels is the method mentioned in Figure 3.

The result is shown in Figure 13 and Figure 14. Obviously, the proposed method alleviates the lateral chromatic aberration effectively. However, the results of proposed method have slight color fringes compared with the results of multi-channel. This is because the proposed method performed on the output of distortion correction.

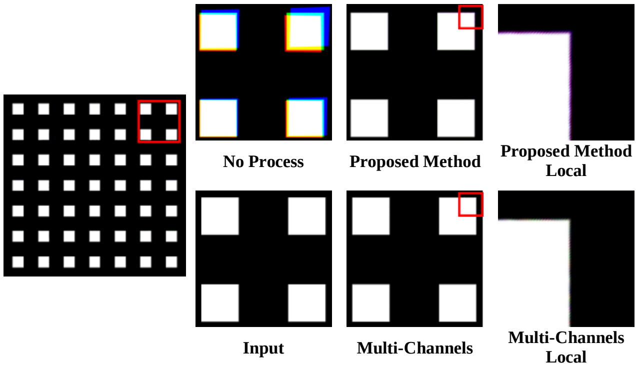

Figure 13. Our Method Result 1

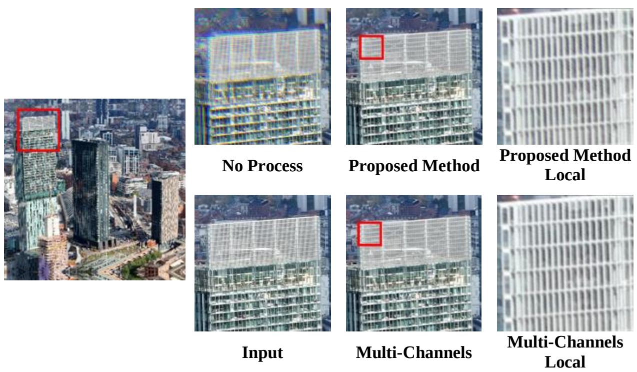

Figure 14. Our Method Result 2

The result of luminance compensation is shown in Figure 15. The proposed solution could correct the aberration without color shift.

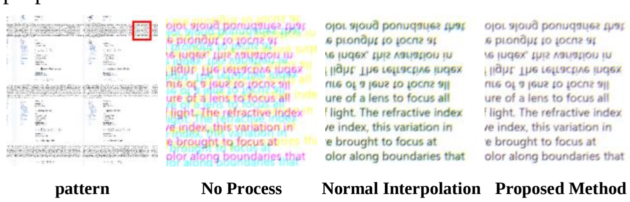

Figure 15. The Result of Luminance Compensation

The result of color edge compensation is shown in Figure 16. The proposed solution could remove the color edge. However, there are slight color fringes along the border.

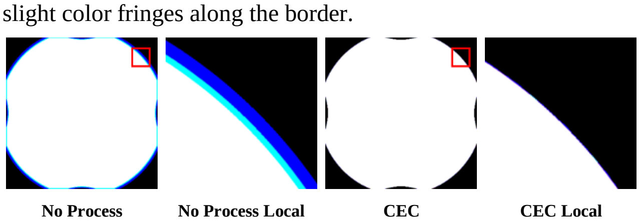

Figure 16. The Result of Color Edge Compensation

5. Conclusion

In this paper, a novel image processing system was proposed to correct the lateral chromatic aberration in VR application. The color edge and color shift issues in VR application were analyzed and the corresponding solutions were designed. Experimental results indicated that the chromatic aberration correction system is scientifically effective. The issues of color shift and color edge were improved a lot.

This system provided a paradigm for correcting the aberration in VR application. It can be widely used in hardware or software processing flows.

6. References

1. Zhan T, Zou J, Xiong J, Liu X, Chen H, Yang J, et al. Practical chromatic aberration correction in virtual reality displays enabled by cost‐effective ultra‐broadband liquid crystal polymer lenses. Adv Opt Mater [Internet]. 2020;8(2):1901360. Available from: http://dx.doi.org/10.1002/adom.201901360
2. Lluis-Gomez A, Edirisinghe EA. Chromatic aberration correction in RAW domain for image quality enhancement in image sensor processors. In: 2012 IEEE 8th International Conference on Intelligent Computer Communication and Processing. IEEE; 2012.
3. Kang SB. Automatic removal of chromatic aberration from a single image. In: 2007 IEEE Conference on Computer Vision and Pattern Recognition. IEEE; 2007.
4. Chung S-W, Kim B-K, Song W-J. Detecting and eliminating chromatic aberration in digital images. In: 2009 16th IEEE International Conference on Image Processing (ICIP). IEEE; 2009.
5. Fryer JG, Brown DC. Lens distortion for close-range photogrammetry. Photogrammetric Engineering & Remote Sensing. 1986 Jan 1;52(1):51–8.
6. Fitzgibbon AW. Simultaneous linear estimation of multiple view geometry and lens distortion. In: Proceedings of the 2001 IEEE Computer Society Conference on Computer Vision and Pattern Recognition CVPR 2001. IEEE Comput. Soc; 2005.
7. Hiswkazu S. image capture apparatus, and method for correcting image quality. US Patent. 8,508,655 B2, 2007.
8. Keys R. Cubic convolution interpolation for digital image processing. IEEE Trans Acoust [Internet]. 1981;29(6):1153–60. Available from: http://dx.doi.org/10.1109/tassp.1981.1163711