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Optical Measurement with Foveated Rendering and Dynamic Compensation in Eye-Tracking Near-Eye Displays

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Abstract

Eye-tracking technology has been widely adopted in the extended reality (XR) industry, particularly in applications such as foveated rendering, eye-tracking interactions, and optical algorithm compensation, enhancing user immersion and providing smooth virtual experiences. For near-eye display systems integrated with eye-tracking capabilities, optical performance metrics such as the Contrast Transfer Function (CTF) and chromatic aberration (CA) vary with shifts in the user's fixation point, rendering traditional measurement methods inadequate for such systems. To address this, this paper proposes a novel approach for measuring CTF based on foveated rendering, as well as a dynamic compensation-based method for assessing chromaticity uniformity and chromatic aberration in eye-tracking near-eye display systems. Experiments are conducted to measure the CTF under both Eye-Tracked Foveated Rendering (ETFR) and Fixed Foveated Rendering (FFR). The results demonstrate that the CTF under ETFR is higher than that under FFR, more accurately reflecting the image clarity perceived by the human eye. Additionally, Chromaticity uniformity shows marked improvement after compensation, with a noticeable reduction in green color shift. The average $\Delta u'v'$ decreases from 0.0092 to 0.0042, suggesting improved chromaticity uniformity. However, chromatic aberration exhibited no significant improvement after compensation.

Author Keywords

Dynamic Compensation; Foveated Rendering; Eye-Tracking; Near-Eye Displays.

1. Introduction

In recent years, near-eye display systems with Eye Tracked Foveated Rendering (ETFR) have emerged [1-4]. Eye-tracking operates by detecting and recording the eye movements, typically through infrared light and cameras that track pupil position. This technology analyzes the user's gaze direction, enabling high-resolution rendering of the gaze area while reducing the resolution of peripheral regions. This approach significantly reduces computational demands without compromising user experience.

Traditional measurement methods can evaluate the Contrast Transfer Function (CTF) when foveated rendering is deactivated [5-6]. However, these methods are unable to simulate human eye rotation to render images clearly within a specific viewing direction when foveated rendering is active. As a result, they fail to accurately reflect the sharpness perceived by the human eye.

Previous research has pointed out that pupil displacement can introduce additional distortions, necessitating algorithmic corrections [7-8]. Certain near-eye display systems employ dynamic image compensation, where eye-tracking technology identifies the gaze area and applies corresponding lookup tables (LUTs) to correct the image in that region, ultimately delivering a

high-quality visual experience to the user. Traditional methods for measuring optical properties typically involve positioning the entrance pupil (iris) of camera at the center of the near-eye display (NED) eye box (eye point), followed by adjusting the viewing direction by rotating around the entrance pupil or the center of the eyeball, located 10 mm behind the entrance pupil [9-10]. However, these methods cannot dynamically assess image quality in the user's gaze area.

This study introduces a comprehensive measurement methodology designed to accurately characterize the CTF with foveated rendering, as well as chromatic aberration and chromaticity uniformity with dynamic compensation. The proposed method effectively represents the images quality perceived by the human eye, where the images have been compensated by image processing algorithms or rendered at high resolution.

2. Method

Previous studies on Near Eye Display (NED) measurements have highlighted the need for optical measurement devices to simulate the optical configuration of the human eye, which includes positioning the entrance pupil of the optical device in front and aligning it with the exit pupil of the NED. Additionally, there are two modes for simulating eye movement: pupil rotation and eye rotation [9] (see Figure 1). Pupil rotation refers to the unnatural rotation of the eyeball. This is the case when the entrance pupil of a 2D array is placed at the fixed eye point. Eye rotation, on the other hand, refers to the rotation of the eyeball around its center, allowing the eye to focus on various field angles. In small viewing directions, both methods can be considered nearly equivalent. However, for large viewing directions, the results from the pupil rotation method do not accurately reflect human eye observations. This discrepancy arises because when the eye focuses on different viewing direction, the displacement of the entrance pupil relative to the eye point can adversely affect the image quality perceived by the observer.

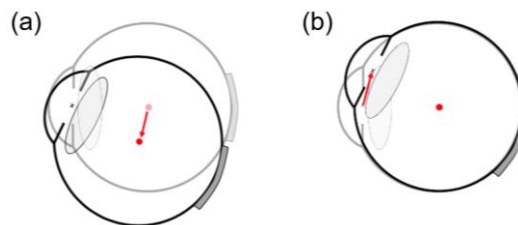


Figure 1. Eye rotation mode. (a) pupil rotation; (b) eye rotation.

This paper presents a measurement method for eye-tracking near-eye displays using the eye rotation mode. First, a measurement system that can be recognized by eye-tracking devices is designed, as shown in Figure 2. This system consists of a motion control unit and an eye-simulating camera. The motion control unit drives the eye-simulating camera to rotate around a point 10 mm behind the

entrance pupil with a rotational precision of 0.1 degrees. The appearance of the eye-simulating camera mimics the characteristics of the human eye, including the cornea, pupil, iris and sclera, allowing it to be recognized by eye trackers just like a real human eye.

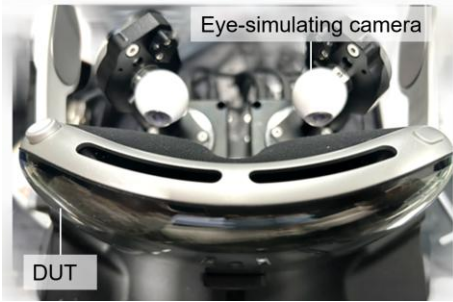


Figure 2. A NED measurement system

The measurement procedure is as follows: the camera is rotated to align the center of the camera with the virtual image in NED, followed by horizontal or vertical movement of the camera to optimize the clarity of the CTF within the eye box [11-12]. Subsequently, eye-tracking calibration of the NED is performed using the camera, with the calibration method identical to that used for real human-eye calibration. Specifically, the motion control unit moves the camera to sequentially focus on each calibration point until successful eye-tracking calibration is achieved. This indicates that the rendering area within the NED will adjust dynamically with the camera's line-of-sight direction. Next, CTF and other test metrics can be performed with the measurement system. Detailed measurement procedures and analysis methods are described below.

2.1 CTF

The CTF measurement based on foveated rendering involves rendering line pairs with different periodicities as test patterns on the virtual image of the NED, as shown in Figure 3 [11]. The measurement range is from -35° to $+35^\circ$, over which the camera rotates and records the CTF within a 2° range at each viewing direction at the right eye. Calculate the CTF (Michelson contrast) using Formula (1).

$$C_{m,i} = \frac{L_{vm,i} - L_{vm,i}}{L_{vm,i} + L_{vm,i}} \quad (1)$$

where $C_{m,i}$ is the Michelson contrast at point i , $L_{vm,i}$ is the maximum luminance in the image at point i , $L_{vm,i}$ is the minimum luminance in the image at point i .

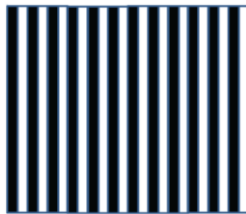


Figure 3. Example of Michelson contrast test pattern

2.2 Chromaticity uniformity

The chromaticity uniformity measurement under dynamic compensation is performed by displaying a W255 white image on the NED. The camera is systematically rotated over a certain range, with chromaticity uniformity being evaluated within a 2° at each viewing direction. Then calculate the $\Delta u'v'$ between each viewing direction and the center viewing direction:

$$\Delta u'v'_{oi} = \sqrt{(u'_i - u'_0)^2 + (v'_i - v'_0)^2} \quad (2)$$

Where u'_i and v'_i represent the chromaticity coordinates of each viewing direction, u'_0 and v'_0 represent the chromaticity coordinates at the center of the virtual image.

2.3 Chromatic aberration

Chromatic aberration (CA) is caused by the dispersion of the optics of the NED leading to a wavelength dependent magnification [11]. CA measurement based on dynamic compensation is conducted by rendering a horizontal and vertical stripe pattern with a specific stripe width on the virtual image of the NED. The camera then rotates through a certain range of viewing direction, and chromatic aberration is measured within a 2° region for each viewing direction. The calculation equations are as follows:

$$CA_{\text{Red-Green}} = \theta_{\text{Red}} - \theta_{\text{Green}} \quad (3)$$

$$CA_{\text{Blue-Green}} = \theta_{\text{Blue}} - \theta_{\text{Green}} \quad (4)$$

Where θ_{Red} , θ_{Green} and θ_{Blue} is the measured angle of the edge for the red, green or blue test pattern, $CA_{\text{Red-Green}}$ and $CA_{\text{Blue-Green}}$ is chromatic aberration of red or blue (see Figure 4).

If the measurements are conducted to assess the performance after dynamic compensation, the foveated rendering or dynamic compensation function of the NED device must be enabled.

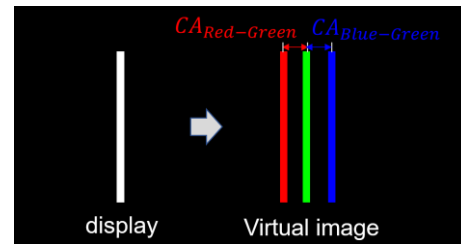


Figure 4. Schematic diagram of chromatic aberration

3. Measurement results

The device under test (DUT) is a commercial head-mounted display (HMD) with eye-tracking. The eye-tracking system in the device not only supports interaction but also enables real-time foveated rendering and dynamic compensation of the gaze area. The monocular FOV of the NED is $96^\circ \times 80^\circ$, with a resolution of 3648×3144 pixels per eye. During measurement, real-time rendering and dynamic compensation can be turned on or off. The entrance pupil of the camera is located 18 mm behind the NED lens.

3.1 CTF measurement results

The Contrast Transfer Function (CTF) of the NED's right eye is measured using the method outlined in Section 2. The difference between enabling and disabling real-time foveated rendering is as follows: when real-time foveated rendering is enabled, Eye Tracked Foveated Rendering (ETFR) renders the gaze area at full resolution, while areas outside the gaze region are rendered at a lower resolution. When the real-time foveated rendering is disabled, Fixed Foveated Rendering (FFR) is used, wherein a high-resolution area is fixed at the center of the screen, and lower resolution is applied at the edges.

The horizontal CTF results based on eye rotation are illustrated in Figure 5. The blue line with pentagram markers represents the CTF under ETFR at a -20° viewing direction, which corresponds to the CTF measured near -20° when the eye is fixated at -20° . The results indicate a declining trend in CTF as the measurement point moves away from -20° , which is visually reflected by the gradual blurring of the "blue" label in the figure. The black curve with square

markers, formed by connecting the peak CTF values at each viewing direction, represents the perceived clarity observed by the human eye under ETFR. The black curve with triangle markers represents the CTF under FFR, which is lower than that of ETFR. The CTF difference between the FFR and ETFR increases with the viewing direction getting wider.

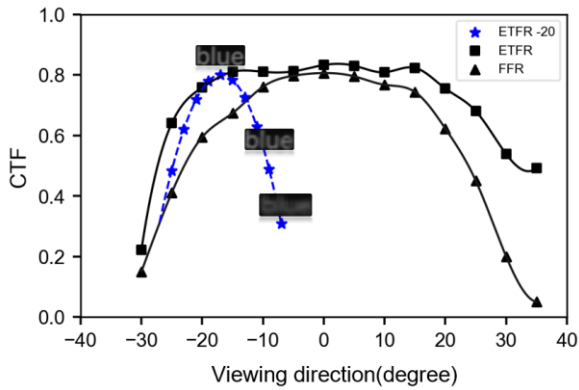


Figure 5. Horizontal CTF curve of ETFR and FFR

3.2 Chromaticity uniformity measurement results

Firstly, the conventional pupil rotation measurement method is applied to the NED in the horizontal viewing direction when dynamic compensation is disabled. The black dots in Figure 6 illustrate the distribution of colors for white at each viewing direction under pupil rotation on the CIE 1976 chromaticity diagram. The color distribution under pupil rotation is relatively concentrated. The black histogram in Figure 7 displays $\Delta u'v'$ of colors at various viewing directions relative to the NED optical axis under pupil rotation. The results demonstrate that chromaticity uniformity of most viewing direction satisfies $\Delta u'v' < 0.0040$, with average $\Delta u'v'$ of 0.0028. However, upon visual inspection, the human eye perceives color shifts of green, which is not reflected in the pupil rotation measurement results.

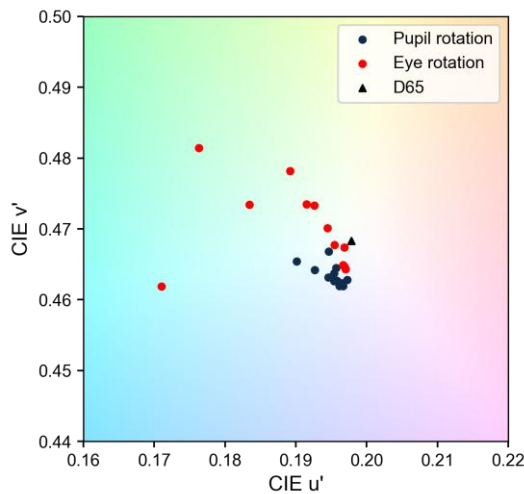


Figure 6. Color distribution of different horizontal viewing directions with pupil rotation and eye rotation in CIE 1976 chromaticity diagram.

Eye rotation more accurately simulates the image quality as perceived by the human eye. The red dots in Figure 6 depict the color distribution under eye rotation when dynamic compensation is deactivated, revealing a more dispersed color distribution.

Notably, certain viewing directions exhibit a greenish color shift during eye rotation. As illustrated in Figure 7, the chromaticity uniformity measured through eye rotation is worse than that of pupil rotation, characterized by a maximum $\Delta u'v'$ of 0.0270 and an average $\Delta u'v'$ of 0.0109. To mitigate the chromaticity non-uniformity, it is usually necessary to employ algorithms for compensation.

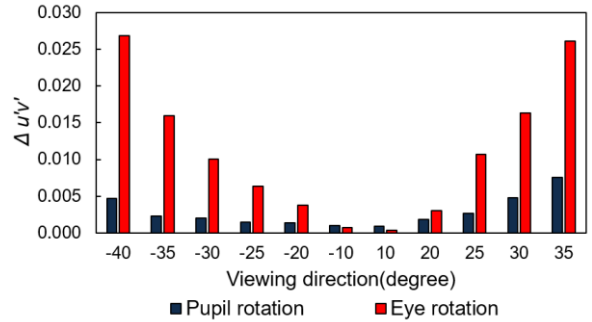


Figure 7. $\Delta u'v'$ of different horizontal viewing directions with pupil rotation and eye rotation.

To measure the chromaticity uniformity after compensation, the dynamic compensation function of the NED device is activated. Figures 8(a) to 8(d) show the color coordinates for a white image at different viewing directions, before and after dynamic compensation. It can be observed that without compensation the left side of the field of view (larger than 30 degrees) exhibit a greenish color shift, with the color coordinates deviating significantly from the center (0°). After compensation, the color coordinates in the -30° to -40° range are closer to the center viewing direction. The right, top, and bottom edges of the field of view that were previously greenish can also be compensated to more closely match the color of the center viewing direction.

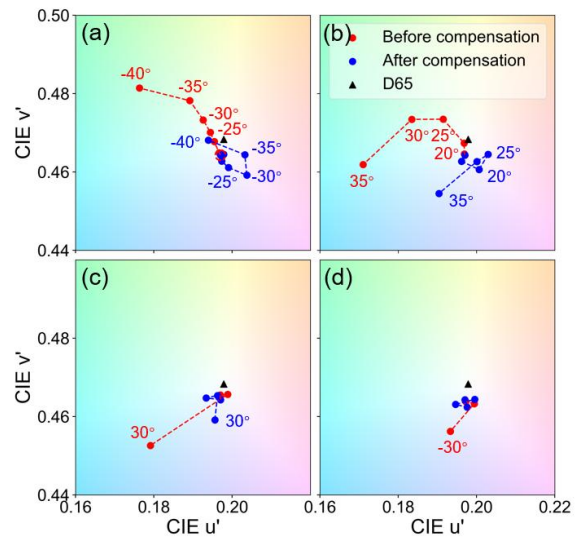


Figure 8. Color distribution of different viewing directions before and after compensation in CIE 1931 chromaticity diagram. The (a) left, (b) right), (c) top, and (d) bottom edges of the field of view

The chromaticity uniformity is assessed by calculating $\Delta u'v'$ for each horizontal viewing directions relative to the center viewing direction, as depicted in Figures 9. Before compensation, the average $\Delta u'v'$ of the 17 viewing directions (including both

horizontal and vertical viewing directions) was 0.0092, and after compensation, the average $\Delta u'v'$ reduced to 0.0042, a decrease of approximately 50%. In conclusion, the chromaticity uniformity after compensation is superior to that before compensation.

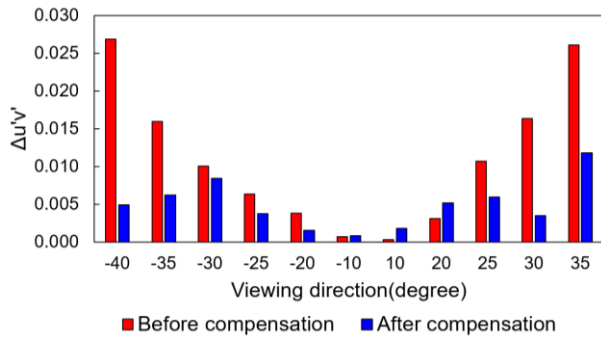


Figure 9. $\Delta u'v'$ of viewing directions across the horizontal fields of view with eye rotation with and without compensation.

3.3 Chromatic aberration measurement results

The chromatic aberration measurement based on dynamic compensation was conducted on the left eye of the NED using the above measurement method. Figure 10(c) and 10(d) show the chromatic aberration before and after dynamic compensation with eye rotation. The maximum chromatic aberration of Red-Green and Blue-Green before compensation are 0.053° and 0.072° , and the maximum chromatic aberration after compensation are 0.080° and 0.041° . This shows that there was no significant change in chromatic aberration before and after compensation.

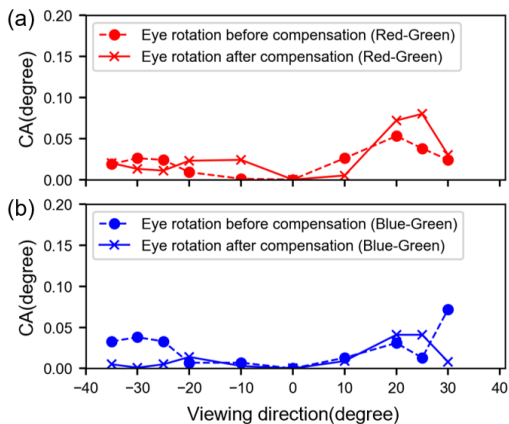


Figure 10. Chromaticity aberration of different horizontal viewing directions. (a) CA of Red-Green; (b) CA of Blue-Green before and after compensation.

4. Conclusion

This paper proposes a measurement method for near-eye display systems with eye-tracking in the eye rotation mode. The method involves measurement of the Contrast Transfer Function (CTF) based on foveated rendering, as well as the chromaticity uniformity and chromatic aberration before and after compensation. The test results show that the CTF with Eye Tracked Foveated Rendering (ETFR) is higher than that with Fixed Foveated Rendering (FFR). Traditional measurement methods can only assess the CTF with FFR, which fails to reflect the actual image clarity perceived by the

human eye. After compensation, significant improvements in chromaticity uniformity were observed, with a reduction in the green color shift and the average $\Delta u'v'$ dropping from 0.0092 to 0.0042. No significant improvement in chromatic aberration was observed before and after compensation. The test results are influenced by a combination of eye-tracking accuracy and dynamic compensation precision. The proposed measurement method is important for evaluating eye-tracking-based near-eye display systems.

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