

Correlation between LCD Dynamic Contrast and Pancake VR Optical System

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Abstract

The LCD with high dynamic contrast does not have a good performance in the pancake VR optical system, which is a major pain point for us. In order to clarify the root cause and improve the adaptability of the LCD and the VR system, the theoretical model is established and the LCD dynamic contrast is further improved. The pain point is solved successfully.

Author Keywords

Dynamic Contrast; LCD; Virtual Reality displays; Pancake

1. Objective and background

With the increasing demand for VR HMD (virtual reality head-mounted display) in various fields^[1-2], the optical system has also been updated and iterated, in particular, the pancake optical system was first proposed in 1968^[3], and it can reduce the overall length of the optical system by folding the light path back several times, which can reduce the thickness of the VR HMD by about 50%, making it thinner and more comfortable to wear for a long time, so the pancake optical system has become the mainstream optical solution recognized by the industry.

When using VR HMD, it is necessary for the optical system to have a high dynamic CR (contrast ratio) in order to enhance the vividness of the display and the sense of reality, but the factors that affect the dynamic CR of the VR system are mainly two parts: the pancake optical system and the LCD module. Mini-LED modules can achieve higher dynamic CR^[4] than traditional ELED modules due to the local dimming of the backlight^[5], but in the actual dynamic CR performance of the VR system, sometimes the advantage of Mini-LED modules is not obvious, we tested the ELED module and the Mini-LED module, from the comparison data in Figure 1, it can be seen that the advantage of the dynamic CR of the Mini-LED module is obvious, which is 2.76 times higher than that of the ELED module, but its advantage decreases to 1.7 times when it is combined with the 1# VR system, and disappears when it is combined with the 2# VR system.

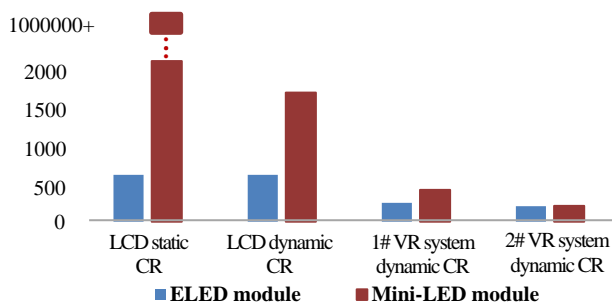


Figure 1. Comparison of LCD CR and VR system CR.

In order to thoroughly analyse the reasons for the above phenomenon, this paper starts from the factors affecting the VR system dynamic CR, firstly, the causes of stray light are analyzed based on the basic architecture of the pancake VR optical system, and the reasons for the decrease or even disappearance of the dynamic CR advantage of the Mini-LED module in the VR

system are clarified, therefore, in order to improve the adaptability of the LCD module and the VR system, the theoretical model is established, and the accuracy of the model is verified by experiments. Secondly, by optimizing the optical design and algorithm design of the Mini-LED module, the LCD dynamic CR is further improved, so that the VR system dynamic CR has a better performance. Finally, the light-emitting model for the ideal display module is established to enhance the brightness and reduce the effect of stray light on the VR system, which can be used to guide the future optical design of the display module.

2. Mechanism Analysis

(a) Architecture of Pancake Optical

For the pancake VR optical system, the core components mainly include quarter-wave plate (QWP), beam splitter (BS), reflective polarizer (RP) and lens, the schematic diagram of the imaging mechanism as shown in Figure 2: The P-light (horizontal linear polarized light) emitted from the LCD is transformed into the circular polarized light by the QWP, and after passing through the BS film, only part of the light can be transmitted into the lens, and then after passing through the QWP, the circular polarized light is transformed into the P-light and arrives at the surface of the RP, but the RP can only transmit the S-light (vertical linear polarized light), so all of the P-light is returned to the surface of the QWP and is transformed into circular polarized light again, but the rotation is opposite due to the effect of the BS film, and after passing through the QWP, the circular polarized light is transformed into S-light and finally enters the human eyes through the RP.

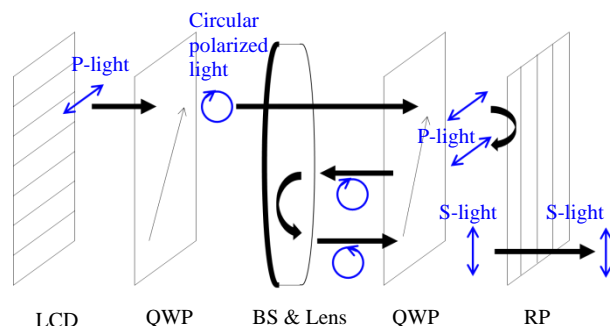


Figure 2. The schematic diagram of the imaging mechanism.

(b) Causes of Stray Light

In the pancake VR optical system, the light is folded back many times, which greatly shortens the overall length of the VR HMD, but at the same time, it also produces other light paths in addition to the light paths of the main image, i.e. stray light^[6], and finally, the imageable stray light that is observed at the pupil position and exiting through the non-designed optical path is called ghost, as shown in Figure 3, and the main causes of stray light are as follows:

- The angle of incidence or wavelength of the light deviates from the working range of the film layer, producing an undesirable polarization state.
- Reflection occurs when the light is directed onto the screen surface of the LCD.
- Influenced by the coating process and the raw materials, there are some reflections on the surface of the film layer and scattering due to the local defects.
- There are reflections on the sides of the lens barrel.

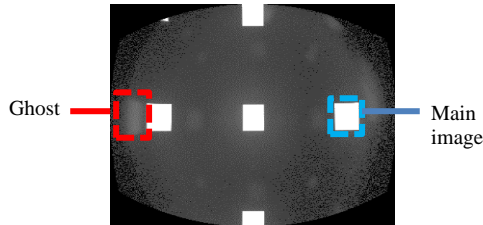


Figure 3. The real shot picture of ghost.

Based on the causes of the stray light, it is known that although stray light can be reduced, but it cannot be avoided, so the severity of stray light directly affects the dynamic CR performance of the VR system^[7], which is also the root cause of the reduction of the dynamic CR advantage of the Mini-LED module in the VR system.

3. Adaptability Improvement between LCD and Pancake VR Optical System

To further study and quantify the effect of stray light on the VR system dynamic CR, the sources of the dynamic L255 brightness and dynamic L0 brightness of the VR system are decomposed and analyzed, and combined with the theoretical model of the VR

system dynamic CR, the adaptability between the LCD and the pancake VR optical system is improved.

(a) Source Analysis of L255 & L0 Brightness

When testing the dynamic CR, L255 and L0 are required to be in the same pattern of the LCD, and the brightness ratio between L255 and L0 is the dynamic CR, and at the same time, the industry usually selects the checkerboard grid as the test pattern for the convenience of evaluation.

Assuming that the dynamic L255 brightness of the LCD is 600nits, and the optical efficiency of the pancake VR optical system is not more than 25%, so the dynamic L255 effective brightness of the VR system is 150nits, and according to the dynamic CR of different LCDs, we can obtain the corresponding dynamic L0 effective brightness of the VR system. However, the actual dynamic brightness is also affected by the stray light of L255 and L0 in the checkerboard grid pattern, and the stray light factor of the VR system is generally between 0.2%~0.4%, which can calculate the dynamic L255 and L0 brightness of the stray light.

From the data in Table 1, it can be seen that the stray light of L255 and L0 has a negligible effect on the dynamic L255 brightness of the VR system, so the dynamic L255 brightness of the VR system is only related to the dynamic L255 brightness of the LCD and the optical efficiency of the VR system. However, for the dynamic L0 brightness of the VR system, it is also related to the stray light generated by the L255 in addition to being related to the dynamic L0 brightness of the LCD and the optical efficiency of the VR system, and the stray light brightness is equal to the stray light factor multiplied by the dynamic L255 brightness of the VR system, due to the different stray light factor of different VR systems, the dynamic CR of the VR system is different even if the LCD is the same.

Table 1. Breakdown of dynamic L255&L0 brightness.

	Dynamic L255 brightness (nits)			Dynamic L0 brightness (nits)		
LCD						
Pancake VR optical system	L255 effective light (25%)	L255 stray light (0.2%~0.4%)	L0 stray light (0.2%~0.4%)	L0 effective light (25%)	L0 stray light (0.2%~0.4%)	L255 stray light (0.2%~0.4%)
Dynamic CR 600:1 (ELED)	150	0.3~0.6	0.002~0.004	0.25	0.002~0.004	0.3~0.6
Dynamic CR 1500:1 (Mini-LED)	150	0.3~0.6	0.0008~0.0016	0.1	0.0008~0.0016	0.3~0.6
Dynamic CR 3000:1 (Mini-LED)	150	0.3~0.6	0.0004~0.0008	0.05	0.0004~0.0008	0.3~0.6

(b) Relationship between LCD and Pancake VR Optical System

Based on the above analysis, when the LCD dynamic CR and the stray light of the VR system are determined, the dynamic CR of the VR system can be theoretically calculated:

$$CR_{lens} = \frac{L_{255-lens}}{L_{0-lens}} = \frac{L_{255-LCD} \times \eta}{L_{0-LCD} \times \eta + K_{straylight} \times L_{255-LCD} \times \eta} \quad (1)$$

$$= \frac{1}{\frac{1}{CR_{LCD}} + K_{straylight}}$$

Among them, the VR system dynamic CR is CR_{lens} , the LCD dynamic CR is CR_{LCD} , the dynamic L255 brightness of the VR system is $L_{255-lens}$, the dynamic L0 brightness of the VR system is L_{0-lens} , the dynamic L255 brightness of the LCD is $L_{255-LCD}$, the dynamic L0 brightness of the LCD is L_{0-LCD} , the efficiency of the VR system is η , the stray light factor is $K_{straylight}$.

To verify the accuracy of the above theoretical model, and the VR system dynamic CR with different stray light factor and different LCD dynamic CR was measured and compared with the theoretically calculated value. The results of the comparison are shown in Table 2.

Table 2. Comparison of theoretical and measured value

CR of LCD K _{straylight}	600		1500	
	Theoretical value	Measured value	Theoretical value	Measured value
0.2%	273	265	375	387
0.4%	176	183	214	208

From the comparison, it can be seen that the theoretical value of the VR system dynamic CR is basically in line with the measured value, and the maximum error at the difference point is 3.8%, because the error rate is less than 5%, the error between theory and measurement is within an acceptable range, so the accuracy verification of the theoretical model passes.

To further explore the relationship between the LCD dynamic CR and the VR system, the VR system dynamic CR after combining with different stray light factors and different LCD dynamic CR can be calculated in bulk using the established theoretical model, the relationship diagram is shown in Figure 4, where the LCD dynamic CR ranges from 500 to 5000, and the stray light factors of the VR system are 0.1%, 0.2%, 0.3% and 0.4%, respectively.

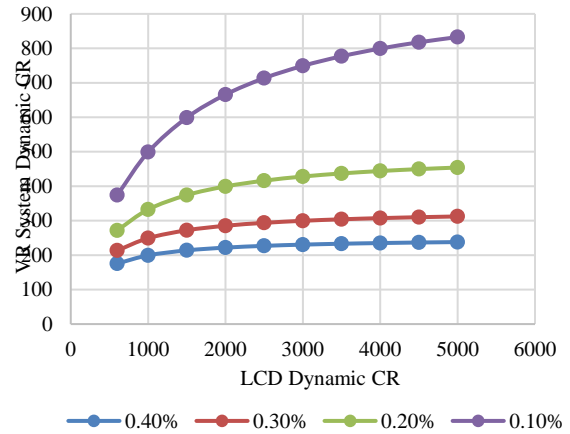


Figure 4. The relationship diagram of the LCD dynamic CR and the VR system dynamic CR with different stray light factors.

From the Figure 4, when the stray light factors are constant (using the same pancake VR optical system), as the LCD dynamic CR continuously increases, the VR system dynamic CR also shows an upward trend, but as the LCD dynamic CR continues to increase, the growth rate of the VR system dynamic CR continuously decreases and gradually flattens out, which means that the advantage of the LCD dynamic CR in the pancake VR optical systems becomes less obvious. If the LCD dynamic CR remains unchanged, as the stray light factor continuously increases, the corresponding VR system dynamic CR gradually decreases, in other words, when different customers' VR systems are paired with the same LCD, the dynamic CR performance of the VR system is different.

In order to achieve better performance of the LCD dynamic CR in the VR system and improve the adaptability between the LCD and the VR system, in the future, according to the customer's requirement for the VR system dynamic CR and the stray light factor, we can use the theoretical model to evaluate and reasonably select the LCD with the best match, which will improve the accuracy and efficiency of the design.

4. Solution Validation

As can be seen from Equation 1, two aspects can be considered to improve the VR system dynamic CR: reducing the stray light factor and improving the LCD dynamic CR, so we focus on analyzing and verifying how to improve the LCD dynamic CR.

Table 3. Validation Results of Optimization Cases.

Solutions	Description	Mechanism & Schematic Diagrams	Results
Narrow-light film	Increase the light-emitting angle by designing the micro-structure for each LED		The LCD dynamic CR is increased by 22%
White dam sealant	Add the white dam sealant between the LEDs to limit the diffusion of the light		The LCD dynamic CR is increased by 31%

(a) Optical Design Optimization

For the Mini-LED display module, the halo is the main factor affecting the LCD dynamic CR, but due to the non-directional and dispersive propagation of light paths by the films such as reflectors, quantum dot films and homogeneous films, the halo phenomenon cannot be avoided, moreover, the larger the halo area is, the greater the effect on the LCD dynamic CR is. In order to optimize the LCD dynamic CR from the optical design, two optimization cases are proposed as shown in Table 3 and verified from the perspective of halo reduction.

(b) Algorithm Design Optimization

A highly dynamic CR algorithm is developed to address the problem of brightness decreasing in high-contrast image display caused by the diffusion characteristics of the backlight: based on the original algorithm, the backlight data is post-processed according to the image content and the power consumption of the backlight, and the display brightness of high-brightness backlight partitions in high-contrast images is increased without increasing the power consumption. At the same time, brightness mapping is performed on liquid crystal pixels to improve the light and shade contrast. By optimizing the algorithm design, the LCD dynamic CR can be increased by 20%. As shown in Figure 5, the dynamic contrast effect of the image is better after the algorithm optimization.

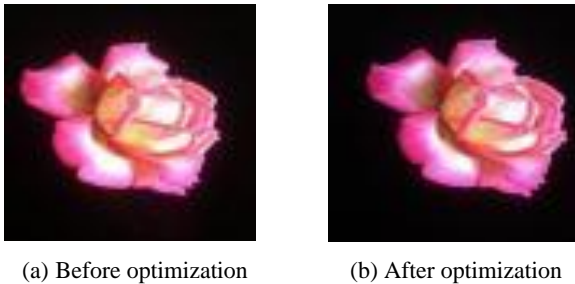


Figure 5. Comparison of VR system images before and after algorithm optimization.

5. Establishment of the Light-Emitting Model for the Ideal Display Module

Based on the above research, for the LCD module, we know that only the light within a certain viewing angle can enter the eye box through the pancake VR optical system, while the light from a large viewing angle is not be used, and even becomes one of the causal factors of the stray light, so improving the backlight's ability to narrow the light and the improve the optical efficiency is the main direction of the research at present. Furthermore, if the light-emitting angle at different positions of the backlight can be customized, i.e., the light-emitting angles at different positions are different and can be matched with the pancake system design in the optical path design, as shown in Figure 6, the light emitted from the LCD module can theoretically be utilized completely by the VR system, and the stray light can be reduced while the brightness is increased, which is the light-emitting model for the ideal display module, and it is also the focus of our follow-up research.

6. Conclusion

In this paper, we analyze that the main reason affecting the VR system dynamic CR is the stray light factor, and derive the

relationship equation between the LCD dynamic CR, the VR system and the stray light factor, the error rate between the measured and the theoretical value is less than 5%, which confirms the accuracy of the theoretical model, and through the model, we find that when using the same VR system, as the LCD dynamic CR increases, the growth trend of the VR system dynamic CR gradually slows down, and if the LCD dynamic CR remains constant, the VR system dynamic CR decreases as the stray light factor increases, which also proves that the design of the pancake VR optical system of different customers is one of the main reasons affecting the dynamic CR performance of the VR system, and at the same time, the theoretical model can be used to accurately evaluate the match between the LCD and the VR system to achieve the optimal design. In addition, the LCD dynamic CR is increased by about 90% by using narrow-light film and white dam sealant in the backlight and combining with the algorithm optimization including backlight filtering and brightness enhancement of the backlight. Finally, to guide the optical design of the future LCD modules, the light-emitting model of an ideal display module is proposed, which will be our next major research direction.

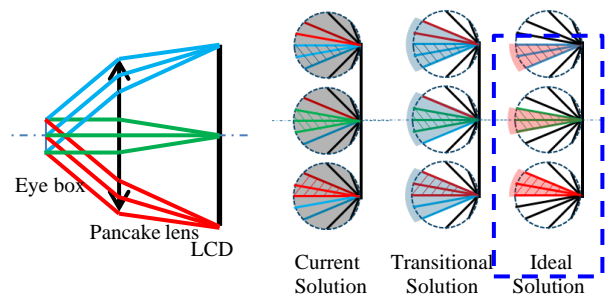


Figure 6. The schematic diagram of the light-emitting model for the ideal display module.

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