Single DLP Optical Engine for Solid Volumetric True 3D Display

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Abstract

According to depth cues of an image, the optical engine of the solid volumetric true 3D display can project a sequence of slices of a 2D image to corresponding display at a set of liquid shutters (LC) locating at different depth. A single DLP optical engine developed for a solid volumetric true 3D display consists of a lamp, reflector, color wheel, hollow integrator, relays, DMD, and projection lens. The simulation results show that the optical engine designed for single DLP volumetric true 3D display satisfies the requirements.

1. Introduction

There has always been a desire to completely display what people see in a real world, which leads the researchers to devote to developing 3D display technologies. Until now 3D display technologies have evolved from stereoscopic to autostereoscopic to nowadays true 3D [1, 2, 3].

True 3D display technologies mainly include volumetric display and holography. Volumetric displays include multiplanar displays and rotating panel displays. Multiplanar displays have multiple display planes to stack up to form a volume while a rotating panel display has a rotating panel to sweep out a volume. As the fact that flat display is today's mainstream display technology, multiplanar display is considered to be more compatible than rotating panel display with flat display. With no mechanical motion, multiplanar display can put on desk in front of a viewer and easier to work with legacy systems.

LC shutters are employed as display panels, which can transmit between transparent state and scattering state. As a key component, the optical engine projects a sequence of slices of a 2D image onto a set of LC shutters locating at different depths. According to what kind of space light module (SLM) is exploited, optical engines (OEs) can be classified into liquid crystal display (LCD), liquid crystal on silicon (LCoS), and digital micro-mirror device (DMD). LightSpace Company has marketed a 3-DMD 3D display [4]. To reduce cost, a single DMD is used in a true 3D display, which is now under development by hefei university of technology (HFUT).

The paper is organized as following: the requirements and theoretical design for an OE are presented in detail in the second part. The third section gives some simulation results. The conclusions are drawn in the final part.

2. Optical Engine Design

A single-DMD based solid volumetric true 3D display mainly consists of an image processing board, an OE, 4 fold mirrors and a set of LC shutters, as shown in figure 1.

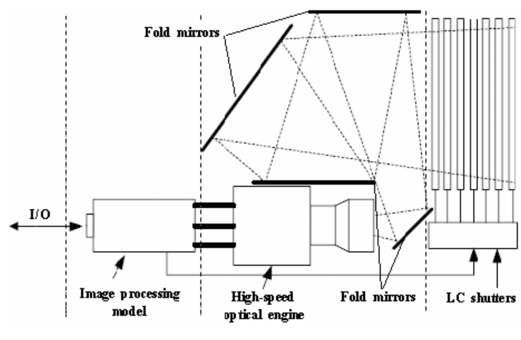

Fig. 1. Schematic diagram of true 3D display

Based on specified algorithm, the image processing board creates a sequence of slices of a 2D image. The slices are projected by the OE at high frequency. Fold mirrors with high reflectivity are involved to reduce the size of the OE. At one time there is only one LC shutter staying in scattering state to enable display the corresponding image slide while others are in transparent states. With the slices of an 2D image displaying on different LC shutters in sequence, a viewer will perceive 3D.

An OE usually includes illumination system, color separation/recombination system, SLM, and projection lens. The schematic diagram of the OE for true 3D display is shown in the figure 2.

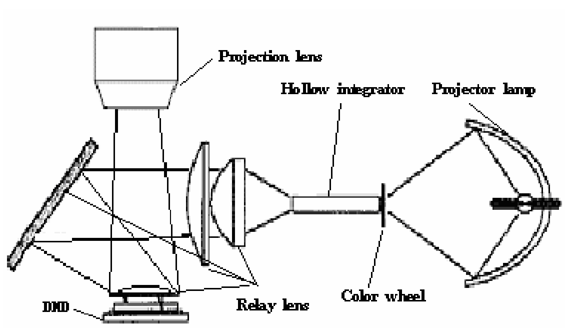

Fig. 2. Schematic diagram of optical engine

A color wheel is exploited to separate white lights into color lights [5]. DMD is used as SLM. A hollow integrator is used to change the circular light spot into rectangular one and uniform the lights. An ellipsoidal reflective bowl is used to match the use of the hollow integrator. The projector lamp is located at the first focus of the ellipsoidal bowl and the color wheel at the second focus. With the limitation of optical structure and the size of the hollow integrator, the light spot outputted from the hollow integrator can not directly illuminate DMD, leading to the involvement of a set of relay lens.

To be used in true 3D display, the OE should have several distinct characters: (1) as the lights from a projector lamp have to transmit a set of LC shutters to reach a viewer, the luminous output should be very high; (2) as a sequence of image slices have to display in sequent on LC shutters, the fresh rate of an OE should be at least 24*20=480Hz for 20 shutters to avoid flicking.

With the use of a single DMD, a color wheel has to be involved to separate white lights from the projector lamp into color lights of red (R), green (G), and blue (B). For 480Hz refresh rate, the frequency of color field of RGH has to be 480Hz, which means a color wheel with RGB section has to rotate at frequency of 480Hz. Until now there are no such color wheels on market. To avoid customizing and reduce cost, an available color wheel of RGBRGB and 4× (240Hz) is employed.

The luminance *L* of a true 3D display is required to be 120cd/m^2 and the active display area is 10 inch (203.2*152.4mm). The solid angle ω could be calculated with the following equation:

$$\omega = \frac{4\pi S}{r^2} = 1.03 \qquad (1)$$

Where, S is the active display area. r is the radium of the equivalent sphere. By the equation 2, the required luminous flux *Lm* is

$$Lm = L \times \omega \times S = 3.83lm \quad (2)$$

With the consideration of (1) 20 LC shutters with the transmission of 75%; (2) 4 reflective mirrors with the reflectivity of 92%; (3) the efficiency of the OE is 20%, the luminous flux output of the projector lamp should be 8429lm. A UHP (ultra high performance) lamp with the power of 200W is chosen [6].

The size of DMD is 0.7 inch, and the max tolerance angle θ is 24 degree. The numerical aperture F is

$$F = \frac{1}{2\sin\theta} = \frac{1}{2\sin 12} = 2.4 \quad (3)$$

The Etendue of DMD is [7]

$$Etendue(dmd) = \frac{\pi A}{4F^2} = 20.68 \quad (4)$$

Where, A is the effective area of the DMD. Abiding by the principle of "Etendue is the constant", the Etendue of the hollow integrator is also equal to 20.68. With the following equations, the width and height of the hollow integrator is set to be 9 and 6.75, respectively.

$$\begin{cases} Etendue(\text{integrator}) = \pi wh \sin{\phi_{\max}}^2 = 20.68 & (5) \\ w : h = 4 : 3 & (6) \end{cases}$$

Where, w and h is the width and height of the hollow integrator, respectively. ϕ is the max divergence angle.

As the reason that a package of a set of LC shutters has a certain thickness, the display areas on each LC shutter increase gradually. To control the size difference of the display area under 10% on the first shutter (close to the projection lens) and the last one (close to the viewer), the distance between the projection lens and the first LC shutter should be

950mm, as shown in figure 3.

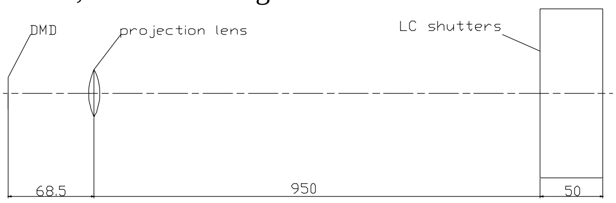

Fig. 3. DMD, projection lens, and LC shutters

For 0.7'' DMD, the parameters of the projection lens are designed as the following:

- Magnification: 14.3
- focal length: 65.36mm
- distance from front focus to film: -4.57mm
- relative aperture: 2.4
- objective distance: 69.93

3. Simulation results

Based on the above design, a single-DMD based true 3D display is simulated, as shown in the figure 4. Some surface and materials properties are defined to better simulate the real applications. The transmissions of LC shutters and reflective mirrors are set to be 75% and 90%, respectively. The projection lamp of a UHP is simplified to a cylinder light source with the luminous output of 10000lm. The property of interior surface of the hollow integrator is defined to be perfect mirror.

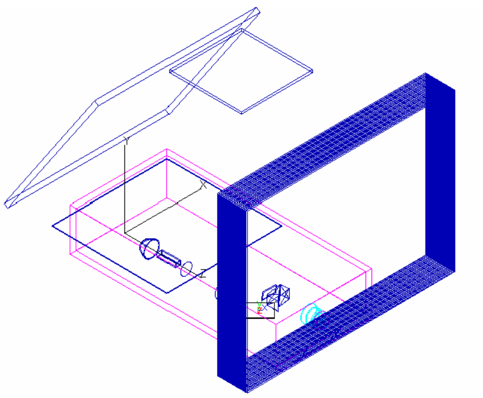

Fig. 4. Simulation model of true 3D display

Figure 5 and 6 are the illuminance maps of the first LC shutter and 20th LC shutter, respectively.

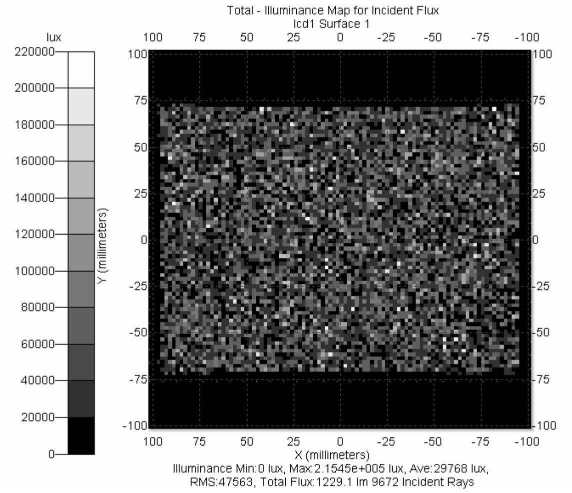

Fig. 5. Illuminance map on 1st shutter

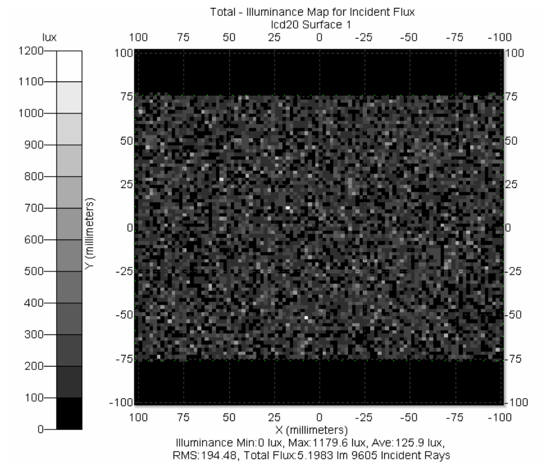

Fig. 6. Illuminance map on 20th shutter

After transmitting 20 LC shutters, only 0.4% of lights can reach the eyes of a viewer. 1 percent increase on the transmission of LC material will lead to the 20 percent increase on luminance, which means the LC transmission on the transparent state is as high as better. However the transmission on the scattering state should be as low as better for clear displaying. One of the future research works will focus on improving the characteristics of LC materials. The luminous flux illustrated in the figure 6 is measured on the surface close to the projection lens on the 20th LC shutter, which means only 3.9lm lights can reach the viewer. With the consideration that the color wheel is not included in the simulation model, the real luminous flux would be less than 3.9lm. Figure 7 shows the transmission of the color wheel that can satisfy the requirements of true 3D display, as discussed above.

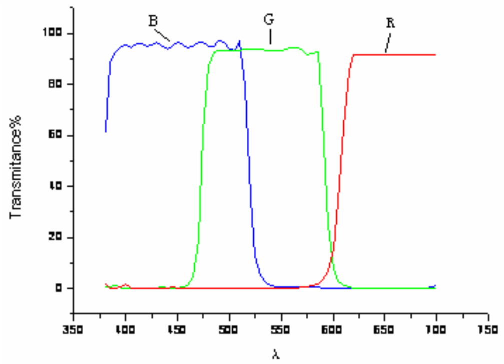

Fig. 7. Transmission of color where

Take the transmission of the color where as 90%, the final luminous flux would be 3.51lm, a little bit less than the required 3.83lm. This could be partly caused by the difference between the assumed efficiency and simulation efficiency of the OE. In the theoretical design discussed above, the OE efficiency is assumed to be 20% and the efficiency in the simulation is 18% ($1229/0.9^4/10000$). As the consideration that the real efficiency of an UHP could reach 60-70lm/W, which means the luminous output should be more than 12000lm (10000lm in the simulation model), the practical luminance of the OE could satisfy the requirement.

4. Conclusion

This paper presents a theoretical design and simulation results of the optical engine for single DMD based true 3D display. Different from common OEs, the true 3D display OE has to provide very high luminous output and high refresh rate. A color wheel with RGBRGB and 4× (240Hz) is chosen to provide color fields at the frequency of 480Hz. The simulation results show the 200W UHP lamp is enough for the luminous requirement of 120cd/m^2. As a set of shutters are stacked up to form a physical volume and provide the 3D feeling, a minute improvement on LC material will help low the requirements for the OE and consequently low the cost.

5. References

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