Eye-tracked three-dimensional display based on laser backlight modulated by spatial light modulator

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**NANYANG
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UNIVERSITY**

SINGAPORE

**EYE-TRACKED THREE-DIMENSIONAL DISPLAY
BASED ON LASER BACKLIGHT MODULATED BY
SPATIAL LIGHT MODULATOR**

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SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

2017

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BASED ON LASER BACKLIGHT MODULATED BY
SPATIAL LIGHT MODULATOR**

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Abstract

Three-dimensional (3D) display technology is a fascinating research topic with wide applications such as 3D visual entertainment, 3D medical imaging and virtual reality, etc. However, the previous commercial solutions have various defects such as great loss of resolution, low brightness, fixed view location and the constraint of wearing special glasses. Glasses-free 3D displays providing 3D scene without any constraints are particularly attractive. In this thesis, two high-resolution autostereoscopic 3D displays are proposed and experimentally demonstrated.

The first prototype is an eye-tracked laser-based 3D display, which is composed of a scanning laser, a ferroelectric liquid crystal spatial light modulator (FLC-SLM) array and a transmission screen. In this proposed system, the scanning laser backlight is modulated by the FLC-SLM array to generate directional backlight. Employing eye tracking technology, the directional backlight is projected on the location of viewers' eye pupils in real-time, which allows multi-viewers to move freely. A prototype system has been set up to verify this idea. The experimental results show that the perceived 3D images have lossless fidelity, high brightness and contrast. The crosstalk of the 3D contents is below 5% which is well acceptable. Viewers can move freely in a wide zone to watch 3D contents without wearing any glasses.

In the second prototype, we proposed a time-sequential LED-based 3D display, consisting of a high-density LED lens array, linear Fresnel lens and a low diffraction LCD. The LED lens array controls the direction of the backlight, which projects convergent viewing zone for viewer's left and right eyes. A prototype has been established to verify this idea. The experimental results demonstrate a full-resolution 3D contents with natural 3D effect high contrast ratio around 300:1 and low crosstalk around 14%.

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1 Introduction

1.1 Motivation

We human beings live in a three-dimensional (3D) world and can perceive 3D scenes because we have binocular vision in nature. Compared with 2D images, the 3D scenes can provide depth cues which enable us to obtain more accurate information to explore and understand the world. Even though great progress has been witnessed in display technologies, we still perceive 2D information from all kinds of liquid crystal displays, such as smart phone, computer and television.

In recent years, the 3D cinemas, 3D televisions, and broadcasters have been developed and greatly influence the way we perceived the world. In addition, the 3D displays have tremendous potential applications in medical and health services, visual entertainment, 3D gaming, education, commercial advertisement and virtual reality, etc. However, numerous challenges and limitations exist in the prevailing 3D display technologies. For example, wearing special 3D glasses, suffering from nausea after watching 3D contents for a long time, huge loss in 3D image resolution and brightness. Therefore, the next generation 3D displays are expected to provide the most nature 3D experience with full resolution, high brightness, low crosstalk and freedom of movement.

Autostereoscopic display is the ideal way out. Autostereoscopic display is also called glasses-free 3D display, which can display stereoscopic images without wearing any glasses. A range of different technologies have been tried to turn 2D display into Autostereoscopic display with low cost, such as lenticular lenses and parallax barriers. Other technologies like volumetric displays and holographic displays are too far from applications because their complicated setup, high cost and poor 3D contents. Design commercial autostereoscopic display system with vivid

3D performance is the target of both industrial companies and research organizations.

1.2 Objectives

In this thesis, we are aiming to design and establish novel eye-tracked glasses-free 3D display systems with full resolution, high brightness and allowing free movement of multiple viewers. The proposed system will overcome the drawbacks of existing 3D displays and be practical in the industry as well as research field. The specific objectives of this thesis include:

1. To design and verify an eye-tracked 3D display system using laser backlight, FLC-SLM array and high resolution screen. This prototype should support users to watch high resolution, high contrast and low crosstalk 3D images without wearing any glasses. In addition, viewers are enabled to move without constraints.
2. To design and verify a directional backlight 3D display system using LED array and high resolution screen. LED-based 3D display has the advantage of low cost and support large size screen. This proposed system should support users watch high resolution 3D content at the optimized distance without wearing any glasses.

1.3 Major Contribution of the Thesis

In this thesis, two novel time-multiplexing 3D displays are proposed, established and demonstrated. Further research works can continue based on these prototypes.

The first prototype is an eye-tracked 3D display system using scanning laser, FLC-SLM array and assembled screen. By employing modulated scanning laser backlight, full-resolution, high brightness and contrast 3D images are obtained. The crosstalk is less than 5%. Moreover, the viewing zone is successfully extended. The proposed method highly facilitates the possibility of laser-based 3D display.

The second prototype is a time-sequential 3D display using a high-density LED-based directional backlight. It is also a 3D display project I participated in during my study. These two prototypes are both time-multiplexed directional backlight 3D displays. They share many technologies such as the same synchronization method. The second prototype is a good reference for the first one. In this prototype, the LED array controls the converging direction of the backlight, which projects left and right 3D images on viewer's eyes. The experimental results demonstrate a full-resolution 3D contents with natural 3D effect, high contrast ratio. This method has great potential in low-cost large autostereoscopic 3D display.

1.4 Organization of the Thesis

Chapter 1 contains the motivation, objectives and major contribution of this thesis.

Chapter 2 presents literature review of various 3D displays including the principle and the state of art research work, especially on time-multiplexed directional backlight 3D displays.

Chapter 3 elaborates the eye-tracked 3D display system using scanning laser, FLC-SLM array and assembled screen. This chapter includes the detailed design of the principle of optical path, input 3D image construction, signal synchronization and prototype setup. Then experimental results are discussed.

Chapter 4 explains the time-sequential 3D display using a high-density LED-based directional backlight. This chapter explains the principle of the directional view method, input 3D image construction, system synchronization and prototype setup. Then experimental results are discussed.

The last part, Chapter 5 is the conclusion of this thesis and gives recommendations for further research based on the two prototypes.

2 Literature Review

2.1 Overview of 3D Displays

In the last few years, tremendous progress in three-dimensional (3D) displays has been witnessed [1]. In the industrial fields, commercial companies like Sony, Philips and so on have released their glasses 3D displays. This kind of 3D displays with special active-shutter or polarized glasses can support several viewers. However, each viewer has to wear glasses with the cost of severe loss in resolution or brightness[2, 3]. Obviously, this solution cannot satisfy the natural viewing requirement of human beings.

Autostereoscopic displays are particularly attractive since they do not require the viewers to wear special glasses. There are various classified autostereoscopic displays, such as multiple view displays, volumetric displays, light field displays, holographic displays and head tracking displays, etc.

2.1.1 Parallax 3D Display

The early autostereoscopic display is the combination of display panel and cylindrical lens array or Parallax barrier. Each vertical cylindrical lens or parallax barrier is corresponding with subarea on the panel. Each image for viewer is the merge of its corresponding sub-images.

Figure 2-1 Optical principle of (a) lenticular autostereoscopic display; (b) parallax barrier autostereoscopic display.

Figure 2-1(a) shows the principle of lenticular autostereoscopic display. Figure 2-1(b) shows the principle of parallax barrier autostereoscopic display. These kinds of displays use specific separating method like lenticular lens or parallax barrier to enable viewers left or right eye to perceive left or right view. The visual fusion of human's brain will generate a sense of stereoscopy. These kind of 3D displays are based on space-multiplexing technique, which divides the viewing space with different viewing zones. For a display panel with a specific resolution, the more viewing zone it divides, the less resolution each viewing zone can be allocated. Therefore, the severe loss of fidelity limits the technology even though they are relatively inexpensive to produce.

Figure 2-2 Multi-view display using slanted lenticular.

Derived from parallax 3D display, multi-view displays generate continuous individual perspective views for left and right eyes of the viewers [4]. The displays are implemented using lenticular screens that consist of an array of cylindrical convex lenses as shown in Figure 2-2. These displays provide motion parallax in the horizontal direction, which is the ability to look around objects. Lm et al. achieve 60 views 3D display using slanted lens sheet and high resolution LCD[5]. They used a 15.1 inch LCD with 3200 by 2400 resolution. A slanted lenticular sheet with angle of 11.3° is attached in front of the LCD to divide the viewing space to 60 viewing zones. Each view has a resolution of 266×480 .

Figure 2-3 Multi-view 3D display with 256 views (a) system principle; (b) prototype; (c) demonstrated 3D images.

However, this approach also suffers from severe resolution loss and limited view angle. To achieve high resolution multi-view display with large field of view, multiple projectors are adopted. Takaki et al. achieve 256 super multi-view 3D display using multiple projectors[6] as shown in figure 2-3. They used multi-view flat-panel 3D displays as the backlight. Sixteen flat-panel 3D displays having 16 views were used to superimpose 256 images on the common screen. The 3D resolution was 256×192 for each view. The screen size was 10.3 inches. The horizontal interval of the viewing zones was 1.3 mm.

2.1.2 Volumetric Display

Figure 2-4 Volumetric 3D displays (a) principle of FELIX 3D display; (b) demonstration of FELIX 3D display; (c) principle of Perspecta 3D display; (d) demonstration of Perspecta 3D display.

Volumetric display generates an object's visual image in 3 dimensions, which is fundamentally different with the 2D images of traditional 3D displays[7]. Image is produced on the rotating surface within a volume of space, thus viewer can focus at a real point from a wide range, which provides ocular accommodation. K. Langhans et al. proposed FELIX 3D system using spiral screen and RGB laser[8]. It mainly consists of RGB lasers, a scanner, and a spiral rotating screen. The modulated RGB laser beams are scanned in two dimensions and focus on the rotating spiral screen in high speed. Due to the persistence of vision, viewers can perceive 3D images. The drawback of this display is the number of voxels is limited. Thus it can't display complicated 3D scenes. Figure 2-4(a) and 2-4(b) show its principle and displayed

image. GE Favalora et al. from by Actuality Systems, Inc. proposed Perspecta volumetric display[9]. This system uses three-chip digital light processing projector to project sliced images on the diffusing screen rotating in high speed. This system can display more than 100 million voxels in 10 inch sphere with a 24 Hz volume refresh rate. The sliced image has a resolution of 768 X 768 and 198 slices are displayed in one rotation. This display has been used in commercial and custom applications. The principle and display image are shown in figure 2-4(c) and 2-4(d). The disadvantages of volumetric displays include: image transparency that the occluded parts of an image are seen through; the display hardware is bulky and complex; the constructed image is limited in a small volume of space.

2.1.3 Light Field Display

Figure 2-5 Compressive Light field display using multi-layer LCDs.

Light field displays replicate the light pattern of the original scene using geometrical optics principles[10, 11]. The light field of one point in space is parameterized by a 7D plenoptic function including the three dimensional spatial position (V_x , V_y , V_z), pitch angle θ , azimuth angle ϕ , wavelength λ and time t . To provide the correct depth cues, abundant light rays should be reconstructed to enter the viewer's pupil from different directions. Thus a huge amount of data is required in light field display.

Compressive light field display uses 4D plenoptic function to parameterize light field, which can be expressed with $L(u, v, s, t)$, where (u, v) and (s, t) are the coordinates of two planes. Gordon et al proposed tensor display using multi-layer LCDs[12]. It is the first time to allow multi-layer, multi-frame light field decompositions. Cao et al. proposed Accelerating decomposition method of light field video for multi-layer displays[13]. However, the 3D image effect can be severely degraded due to the scattering of light and moiré fringes caused by the superposition of two or more periodic components.

2.1.4 Holographic Display

Figure 2-6 Principle of holographic display.

Holographic display is regarded as true 3D display, which reproduces the original wavefront using light interference to generate the true 3D image. Holographic displays are most promising to provide a true 3D scene with perfect reproduction of both amplitude and phase of 3D images. D. E. Smalley et al. proposed the holographic video display as shown in figure 2-7 [14]. They use spatial light modulator based on anisotropic leaky-mode couplers to achieve low-cost, high-performance holographic video display.

Figure 2-7 Holographic video displays (a) prototype; (b) display effect.

Although techniques for producing static images are mature and some stunning results can be obtained, the production of moving images is still problematic due to the large amount of data that must be processed and displayed. The approach is complex and expensive which requires a huge amount of data processing on image acquisition, transmission and display. Also it is limited by the view angle of holographic material.

2.2 Time-multiplexed Directional Backlight 3D Display

In general, autostereoscopic displays are divided into the time multiplexed, spatial multiplexed principles[15]. Spatial multiplexed displays, such as the lenticular or parallax barrier autostereoscopic displays, suffers from several defects like low efficiency, degraded image and narrow viewing angle. The image resolution of each view is inversely proportional to the number of views. This is the fundamental drawbacks of Spatial multiplexing autostereoscopic displays. As for volumetric display, light field display and holographic display, these technologies are far from mature, which can only be found in research work. They have many drawbacks such as low image qualities, complicated structures, and high cost. For example, volumetric displays need multiple projects or complicated rotation mechanism, light field displays need multi-layer display panels and holographic displays require

collimated laser source and holographic materials. These drawbacks prevent them from commercial market. On the contrast, Time-multiplexed directional backlight 3D displays provide high resolution images using commercial liquid crystal display, field lenses, and common light sources such as LED and laser. Therefore, time-multiplexed directional backlight 3D display can be a tradeoff that provides high resolution 3D images with low cost.

Travis et al. firstly proposed the time-multiplexed monochrome 3D display to obtain a laterally multiplexed 3D image[16]. They used a liquid crystal shuttering element to direct image to different zone in front of the display. Moore et al. proposed the colorful 3D display based on the Travis's version[17]. They developed a 6 view full color autostereoscopic display with a resolution of 384 by 288 for each view. Sasagawa et al. proposed a compact stereoscopic display using a double-sided prism sheet [18]. The dual directional backlight can change the direction of light at high speed and has thin, light-weight, simple structure, which is suitable for mobile devices.

Figure 2-8 (a) Schematic of a directional backlight with a switching LCD; (b) demonstrated photographs at the position of left and right eyes.

K. -W. Chien et al. proposed a time-multiplexed 3D display based a fast-switching LCD. In this case, a grooved light guide and an asymmetric focusing foil are combined to redirect the backlight[19]. Figure 2-8(a) shows the schematic of the proposed 3D display and Figure 2-8(b) shows the demonstrated photographs for left

and right eyes. The measured crosstalk of the backlight module with a LC panel is less than 6%.

Figure 2-9 (a) Schematic of MUTED LCOS 3D display and (b) displayed image.

Phillip et al. developed autostereoscopic displays based on stacked lens array that can steer the direction of backlight toward viewer's eyes[20, 21] . This project is named “MUTED” which is the abbreviation of “Multiple-User Three-dimensional Television Display”. It uses a liquid crystal on silicon (LCOS) projector and field lens arrays to generate directional backlight. Multiple users can be supported by incorporating an eye tracker. Figure 2-9 (a) shows the schematic of the display and Figure 2-9 (b) shows the displayed image.

Figure 2-10 Time-multiplexed laser-based 3D displays (a) system principle; (b) displayed images.

A multi-user head tracked directional backlight display[22] has been constructed at Sun Yat-Sen University. This uses a matrix of around 1,000 white LEDs to direct light through an array of vertically aligned linear Fresnel lenses to

serve as the backlight for an LCD panel. The performance is good but work is ongoing on improving the homogeneity of the backlight and extending the field of view. In addition to use the LEDs as a backlight, laser sources have been widely utilized in many fields. Recently, laser-based 3D displays combined with micro-electro-mechanical systems (MEMS) have been suggested to offer high resolution and large depth 3D images [23-26]. As shown in figure 2-9, Reitterer, J. et al. proposed a modular autostereoscopic multi-view laser display using laser diodes and MEMS, which can support thousand viewing zones theoretically[24].

To make a summary, the advantages and disadvantages of these 3D technologies are listed in the Table 2-1 as below.

	Pros	Cons
Parallax 3D display	Slim. Low cost. Easy to scale up.	Loss of half the resolution. No motion parallax. No accommodation. Cause fatigue.
Multi-view 3D display	Limited motion parallax.	Loss of spatial resolution by a factor of view number.
Volumetric 3D display	360 degree motion parallax. Accommodation. No fatigue.	Limited resolution. Limited display volume. Image transparency. Complex and bulky. High cost.
Light field display	Limited motion parallax. Accommodation.	Degraded image. Huge operations for rendering contents.
Holographic display	Motion parallax. Accommodation. No fatigue.	Low resolution. Single color. Complex and bulky. Very high cost.
Time-multiplexed directional backlight 3D display	Lossless resolution. Limited motion parallax with eye tracker. Low cost.	No accommodation. Cause fatigue.

Table 2-1 Pros and cons of the existing 3D display technologies.

3 Eye-Tracked Three-Dimensional Display Based on Laser Backlight Modulated by Fast Spatial Light Modulator

3.1 Introduction

We proposed an eye-tracked 3D display using modulated laser-based backlight, which consists of a scanning laser module, a ferroelectric liquid crystal spatial light modulator (FLC-SLM) array module, an assembled liquid crystal display (LCD) module. The scanning laser backlight is modulated by the FLC-SLM array to generate directional backlight. By means of eye tracking technology, the directional backlight is projected on the location of viewers' eye pupils in real time, which allows multi-viewers to move freely. A prototype system has been established to verify this idea. The experimental results show that the fidelity of the 3D image is lossless with high brightness and contrast. The crosstalk of the 3D contents is below 5% which is acceptable. Viewers are enabled to move freely in a wide zone to watch 3D contents without wearing any glasses. The main contributions of this study are as follows: (1) the image reconstruction scheme is improved, giving high-quality low-crosstalk 3D images; (2) based on the implementation of a reliable eye-tracking algorithm, the viewing freedom is extended by using a depth camera to detect the location of the user; (3) different perspectives of the viewing images can be observed with motion parallax in real time; (4) a synchronization scheme has been developed to ensure minimum crosstalk.

3.2 System Overview

Figure 3-1 System overview of eye-tracked 3D display using scanning laser backlight.

Figure 3-1 shows the system overview of the proposed eye-tracked 3D display system based on scanning laser backlight, which is composed of three main modules: the scanning laser module, the relay transfer subsystem and the transmission screen module. The scanning laser module consists of a laser source and a galvanometer. The relay transfer module has two field lenses (L1 and L2), a horizontal diffuser (H-diffuser), a vertical diffuser (V-diffuser) and one-dimensional FLC-SLM array. In particular, the custom-fabricated FLC-SLMs have 256 narrow vertical pixels that can modulate the amplitude of light with the two states: transparent and opaque. The scanning backlight from the laser module can only pass through the apertures, which are in the transparent state. The transmission screen module consists of four main components: two field lenses (L3 and L4), a Gabor Superlens[27, 28] and a V-diffuser. Additionally, these components are arranged side by side to make it more compact in size. The coherent modulated laser beam is incident into the scanner at an angle of 45° and then is transferred to the field lens L1 as a uniform light line. The field lens L1 combined with the H-diffuser focuses the diffused beam onto the FLC-SLMs as a horizontal line such that at all times during the scan the complete width of the FLC-SLM is lit from a source that is traversing L1 as it is located at its

focal plane.

After exiting the FLC-SLM array, the light beam is expanded in the vertical direction and projected to the transmission screen module via another field lens L2 and V-diffuser. The position of the transmitting apertures on the FLC-SLM is decided by the output of the eye tracker which detects the locations of the viewers' eyes in real time. The light beam transmits through the LCD screen, and finally converges at the user's eye over the scanning period. A high resolution LCD is in charge of playing the time sequential 3D content in which right and left frames are displayed, alternately. Two converging light beams are generated at viewer's left and right eyes. Viewer can observe 3D images without using special glasses when the backlight scanning at fast refresh rate.

3.3 Principle of 3D Display based on Laser Backlight

Figure 3-2 The proposed 3D display system is represented using entrance and exit pupil surfaces.

The directional characteristic of the transmitted beam is depicted in figure 3-2. The general optical components are represented by the entrance and exit planes. This figure also enumerates the symbols which are used in the mathematical derivation of our system. M_t and M_s are the aperture size of the FLC-SLM array in both the tangential and sagittal planes, and V_t and V_s are the viewing zone in the tangential

and sagittal planes, respectively. The light ray is transmitted through L_1 and H-diffuser and expanded in the sagittal plane. After passing through the FLC-SLM aperture, the light beam is spread in the tangential direction and then reaches the transmission screen that it used to converge the light beam to a certain region in the tangential plane, meanwhile, the viewing zone is also enlarged by the V-diffuser to avoid the narrow viewing zone in the tangential plane. Particularly, unlike the conventional imaging system, the characteristic of the proposed transmission screen demonstrates that the viewing zone is produced on the same side of the axis as the FLC-SLM apertures. Moreover, the light beam is magnified by the transmission screen in the sagittal plane to increase the horizontal viewing zone.

Figure 3-3 The mapping of rays angles between light source space and viewing space.

In our demonstration, four circle Fresnel lenses, whose focus lengths are f_1 , f_2 , f_3 and f_4 , act as a single field lens, and assumed free of all Seidel aberrations. Since the laser scanning module is dedicated to form a uniform laser line on the field lens L_1 plane, the maximum scanning angle is given by:

$$\theta_s = \arctan\left(\frac{W_1}{2 \times D_1}\right) \quad (3.1)$$

where D_1 is the distance between laser source and the field lens L_1 , W_1 is the width of the light line on the field lens L_1 plane, as shown in figure 3-3. Based on the law of geometrical optics, the optimal position of FLC-SLMs is calculated by Eq. (3.2),

and then the position of the transmission is expressed by Eq. (3.3) if the relation between the field lens L_1 and the FLC-SLMs is written as:

$$\frac{1}{D_1} + \frac{1}{D_2} = \frac{1}{f_1} \quad (3.2)$$

$$\frac{1}{D_2} + \frac{1}{D_3} = \frac{1}{f_2} \quad (3.3)$$

where D_2 is the distance between L_1 and FLC-SLMs, D_3 is the distance between field lens L_2 and transmission screen. Additionally, the maximum width of LCD is decided by Eq. (3.4):

$$W_s = \frac{W_1 \times D_3}{D_2} \quad (3.4)$$

Figure 3-4 (a) Ray trace modeling for directional backlight using the transmission screen in the sagittal plane; (b) close-up view of the Gabor superlens in the sagittal plane.

The transmission screen is aimed to magnify and project the image of the FLC-SLMs to the viewing zone. Figure 3-4 shows the propagation of rays through the transmission screen in the sagittal plane. Two cylindrical microlens arrays (MLAs) are used between two field lenses. Generally, the analysis of ray propagation through MLA can be uniquely carried out by transfer matrix method or so-called ABCD matrix method[29, 30]. According to the principle of image formation for paraxial rays in geometrical optics, any optical element or optical system can be described

by a 2×2 ray tracing matrix. The input and emergent rays can be represented by the ray height and the slope angle:

$$\begin{bmatrix} x_{out} \\ \theta_{out} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} x_{in} \\ \theta_{in} \end{bmatrix} = \begin{bmatrix} M_{11}x_{in} + M_{12}\theta_{in} \\ M_{21}x_{in} + M_{22}\theta_{in} \end{bmatrix} \quad (3.5)$$

The subscripts “in” and “out” designate the input and emergent rays on the transmission screen system respectively. Consequently, the transfer matrix M of the transmission screen is a product of the transfer matrixes of the field lenses, MLA, MLA thickness Δ , distance D_3 , and optimal viewing distance D_4 .

$$\begin{aligned} M &= M_{D_3} \times M_{L_3} \times M_{MLA_1} \times M_{\Delta} \times M_{MLA_2} \times M_{L_4} \times M_{D_4} \\ &= \begin{bmatrix} 1 & D_3 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_3} & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_{MLA_1}} & 1 \end{bmatrix} \begin{bmatrix} 1 & \Delta \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_{MLA_2}} & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_4} & 1 \end{bmatrix} \begin{bmatrix} 1 & D_4 \\ 0 & 1 \end{bmatrix} \end{aligned} \quad (3.6)$$

where f_{MLA1} and f_{MLA2} are the focal lengths of the MLA layers, and it is given by:

$$f_{MLA(i)} = \frac{R_i}{(n_i - 1)}, \quad (i = 1, 2) \quad (3.7)$$

where R_i and n_i are the radius and the index of refraction of the i^{th} MLA, respectively.

If, for simplicity, D_3 and D_4 are set instead of f_3 and f_4 . Eq. (3.6) can be reorganized as follows:

$$M_{11} = \frac{1}{f_{MLA_1}} + f_3 \left(\frac{1}{f_4} + \frac{1}{f_{MLA_2}} \right) \left(1 - \frac{\Delta}{f_{MLA_1}} \right) \quad (3.8)$$

$$M_{12} = -\frac{f_4}{f_{MLA_1} f_{MLA_2}} \left(f_{MLA_2} + f_3 (f_{MLA_1} - \Delta) \right) \quad (3.9)$$

$$M_{21} = -\left(\frac{1}{f_3} + \frac{1}{f_{MLA_1}} + \frac{1}{f_{MLA_2}} + \frac{1}{f_4} \right) + \Delta \left(\frac{1}{f_3} + \frac{1}{f_{MLA_1}} \right) \left(\frac{1}{f_4} + \frac{1}{f_{MLA_2}} \right) \quad (3.10)$$

$$M_{22} = -f_4 \left(\left(\frac{1}{f_3} + \frac{1}{f_{MLA_1}} \right) \left(1 - \frac{\Delta}{f_{MLA_2}} \right) + \frac{1}{f_{MLA_2}} \right) \quad (3.11)$$

As shown in figure 3-4 (a), a cone of light emanating from the same point at the FLC-SLM aperture that has a different input ray angle θ_{in} must converge at the same position on the viewing zone. It is indicated that the ray height x_{out} is unrelated to the angle θ_{in} . The condition requires input ray independent is valid only for the case of $M_{12}=0$. Substituting Eq. (3.8) in Eq. (3.5) further simplified the equation. The transverse magnification of the transmission screen is then defined to be:

$$\Gamma = \frac{x_{out}}{x_{in}} = M_{11} \quad (3.12)$$

The designed parameters of the field lenses and the MLAs should meet the condition that $M_{11}>0$. Therefore, the FLC-SLM aperture and viewing zone are produced on the same side of the optical axis. The viewing zone size in the sagittal plane is given:

$$V_s = \Gamma M_s \quad (3.13)$$

Based on the law of geometrical optics, the width of the viewing region is given:

$$W_4 = \Gamma W_2 \frac{D_4}{D_3} \quad (3.14)$$

On the other hand, the emergent ray is independent the input ray height x_{in} , yielding $M_{21} = 0$. Substituting Eq. (3.11) in Eq. (3.5) further simplified the equation. The angular magnification of the transmission screen in the sagittal plane has the following form:

$$\eta = \frac{\theta_{out}}{\theta_{in}} = M_{22} \quad (3.15)$$

Eq. (3.15) indicates that angular magnification only occurs in the sagittal plane.

Figure 3-5 (a) Ray trace modeling for transmission screen in the tangential plane; (b) closed-up view of the Gabor superlens in the tangential plane.

Figure 3-5 shows the propagation of the rays through the transmission screen in the tangential plane. The light beam with its axes along the axes of the MLA is not changed. Therefore, the viewing zone size in the tangential plane is given as follows:

$$V_T = M_T \times \frac{D_4}{D_3} \quad (3.16)$$

Figure 3-6 principle of the Scanning laser backlight: (a)-(c) Backlight, which transmits through right aperture and finally converges to the observer's right eye, scans over the transmission screen from left to right side in δ second; (d)-(f) Backlight, which converges to the observer's left eye, scans over the transmission screen in the next δ second.

The schematic shown in figure 3-6 depicts the behavior of the position of viewing point depending on the location of FLC-SLM. The symbol ' δ ' denotes half the refresh rate of LCD screen. The transmitted FLC-SLM pixels form a viewing

zone, because the viewer is located at the conjugate plane of FLC-SLMs, each FLC-SLM pixel generates a corresponding viewing point at the conjugate plane. In figure 3-6 (a)-(c), the backlight scans over the transmission screen from left to right side in δ second. At one moment, only one vertical bar of the image can be seen by the viewer. The rays emitted from the transmission screen that converge to the right eye viewing zone. Due to the effect of persistence of vision, viewer can see the full image on the LCD. At next δ second, the rays transmit through another pixel of FLC-SLM. After emitting from the transmission screen, the rays converge to the left eye viewing zone when the backlight scans over the transmission screen from right to left side as shown in Figure 3-6 (d)-(f).

Figure 3-7 Illustration of viewing zone characteristics when the FLC-SLMs (a) focus point is at the FLC-SLMs plane; (b) focus point shifts in -z direction; (b) focus point shifts in z direction.

The ideal conditions that FLC-SLMs located at the focal plane of field lens L_1 is shown in Figure 3-7(a). Actually, the focal point of field lens L_1 is not necessarily located at the FLC-SLMs plane, it can be modulated by the FLC-SLMs to focus on the left or right sides, which is named virtual object. Therefore the corresponding viewing zone for viewer displaces from the conjugate plane of the FLC-SLMs plane depending on which side of the virtual object is located. As shown in Figure 3-7(b) and Figure 3-7(c), if the aperture on FLC-SLMs shifts along the indicated location during the scanning period (t_1 to t_3) of the backlight, virtual object can be generated on the left or right side of FLC-SLMs plane. In this way, viewer can move in the z -direction in certain range.

3.4 Construction of Input 3D Image

Figure 3-8 System block diagram of 3D image reconstruction for time-sequential 3D display.

As described above, the time-sequential images for left and right eyes are applied for the scanning laser-based backlight in the proposed 3D display. Here, the process

of images recorded is shown in Figure 3-8. In our demonstration, Unity3D[31] is used to construct the images. Two virtual cameras, simulating human eyes, are assigned to capture objects. The distance between the virtual cameras is around 65 mm, equivalent to the human interocular distance, and the virtual cameras to objects is the optimum viewing distance. The images for two views are simultaneously captured by the virtual cameras. Furthermore, there two sets of captured images are interpolated together and displayed in the sequence frame-by-frame on the LCD panel.

3.5 System Synchronization

Figure 3-9 Schematic diagram of the proposed system synchronization method.

Because the left and right viewpoints are scanned in time sequence, each component of the proposed system must be synchronized accurately to ensure each eye of viewer observes the correct image intended for it.

Figure 3-9 shows the framework of the synchronous controlling unit established in house. It consists of camera, workstation, field-programmable gate array (FPGA) control board, Laser, scanner, FLC-SLMs and LCD. The workstation is dedicated for collecting viewer's position data from eye tracking camera, and then the FPGA obtains the data of the viewer's position via a USB port. The 3D video source is streamed to the FPGA through HDMI cable. FPGA module is in charge of driving and synchronizing other blocks. Inside the FPGA, video stream is buffered into the

codec module, where the start signal (VSYNC) of each frame is detected for system synchronization. Then the 3D video is played on the LCD screen. While the VSYNC signal is captured, three modules for laser modulation, scanner waveform and FLC-SLM pattern are triggered at the same time.

Figure 3-10 shows the timing diagram of the signals in the time sequential method applied to the laser, scanner, FLC-SLM apertures and displayed images. Because the FLC-SLM needs equal “on” and “off” time to perform the DC balance in one period, the laser and scanner are modulated with waveforms of 50% duty cycle. The laser is driven by a rectangular waveform. Synchronously, the scanner is driven by a typical sawtooth waveform. As shown in Figure 3-10, the durations t_1 , t_2 , t_3 , t_4 , t_5 are equal to 50% of the refresh period the LCD screen. During the period t_1 , the FLC-SLM aperture for left eye is switched on while the FLC-SLM aperture for right eye is switched off; at the same time, the image for left eye is displayed on the LCD screen. The FLC-SLM performs DC balance and scanner retraces during the period t_2 . In the same way, FLC-SLM aperture for right eye is switched on while the FLC-SLM aperture for left eye is switched off during the period t_3 , and then the image for right eye is displayed on the LCD screen. The scanner also retraces during the period t_4 . A new cycle is started from the period t_5 .

Figure 3-10 The ideal timing diagram of the signals in the proposed 3D display system.

3.6 Prototype Setup

Figure 3-11 Optical elements used in the proposed system. (a) laser and scanner; (b) Fresnel lens L_1 ; (c) Fresnel lens L_2 ; (d) FLC-SLM; (e) $10^\circ \times 2^\circ$ horizontal diffuser; (f) $15^\circ \times 2^\circ$ vertical diffuser; (g) depth camera for real time eye-tracking.

In order to verify the feasibility of the proposed idea, an experiment with the prototype system was conducted. The components used in the proposed 3D display are illustrated in Figure 3-11. Figure 3-11(a) presents a solid state 556 nm green laser module and a galvanometer scanner with maximal scanning angle of 40° and round trip time period between $100 \mu\text{s}$ and $200 \mu\text{s}$. Figures 3-11(b) and 3-11(c) are the circle Fresnel lenses which have focal length of 250 mm and 330 mm respectively. Figure 3-11(c) shows a custom-fabricated one-dimensional FLC-SLM. Each FLC-SLM has 32 pixels, and the active aperture of each FLC-SLM is approximately $37.5 \text{ mm} \times 20 \text{ mm}$ (W×H). Two elliptical diffusers with $10^\circ \times 2^\circ$ and $15^\circ \times 2^\circ$ diffusion angles are employed to generate uniform distributed viewing area. The light beam emitted by a laser source is spread in one direction as demonstrated in Figure 3-11(e) and 3-11(f). An Intel RealSense (SR300) [32] depth camera for eye tracker is shown in Figure 3-11(g).

Figure 3-12 Custom fabricated FPGA driver board with 8 addressed FLC-SLMs.

Figure 3-12 shows the custom fabricated FPGA driver board to drive FLC-SLMs. It has 8 FLC-SLMs for forming 256 pixels, and the active width is about 300 mm. The viewer's location corresponding XYZ values is captured by the depth camera and the tracking data is transmitted to workstation through USB 3.0 port. The X-coordinate and Y-coordinate values are transferred to FPGA by the workstation via the USB port in real time. Meanwhile, 3D video data is sent to FPGA through HDMI input port. The VSYNC signal from the input video stream is collected and then send to LCD screen through HDMI output port. The other driver modules are triggered to operate when the VSYNC signal is collected. The laser driver using a digital buffer to generate a square digital waveform in order to modulate the laser output. While the scanner driver using a digital to analog convertor that is driven by FPGA, which is capable to form an analog sawtooth waveform aiming to drive the scanner.

Figure 3-13 (a) Intensity of FLC-SLM with bright and black state at different driving voltages; (b) contrast ratio of FLC-SLM at different driving voltages.

The measured intensity profiles with bright and black states of the FLC-SLMs are plotted in Figure 3-13(a) as a function of driving voltage. Figure 3-13(b) shows the contrast ratio, which is calculated with respect to the corresponding values of the intensity at bright and black states. The results show that the contrast ratio varies from 70 to 240 when different driving voltages are applied. It is demonstrated that the FLC-SLM has excellent performance as an optical switch. Because the used electrically addressed FLC-SLMs can only be driven by bipolar voltages, the SLM driver consists of a high voltage switch array driven by FPGA, which can translate the digital waveform to ± 10 V bipolar waveform. FPGA generates the corresponding apertures of FLC-SLM according to the tracking data from depth camera in real time.

Figure 3-14 Transmission screen subsystem using a Gabor superlens and two field lenses. (a) optical layout of the Gabor superlens design in sagittal plane; (b) optical layout of the Gabor superlens in tangential plane; (c) close-up view of the Gabor superlens from plot (a) to show the detailed optical configuration; (d) assembled transmission screen using the fabricated Gabor superlens and field lenses L_3 and L_4 .

Figures 3-14(a) and 3-14(b) show the optical layout of the designed Gabor superlens in both the sagittal and tangential planes, and the optical performance is validated by means of ray trace simulations conducted by commercial lens design software Zemax. Figure 3-14(c) shows a close-up view of the Gabor superlens from Figure 3-14(a), it indicates that the designed Gabor superlens is composed of two MLA layers attached together. In Figure 3-14(a) the incident rays focus at the secondary cylindrical MLAs side and then emergent with a magnified angle. The angular magnification factors in the sagittal and tangential planes of our developed Gabor superlens can be expressed by:

$$\theta_o^s = 4\theta_i^s \quad (3.17)$$

$$\theta_o^t = \theta_i^t \quad (3.18)$$

Subscripts “i” and “o” are used to denote incident and emergent rays on the Gabor superlens respectively shown in Figures 3-4(b) and 3-5(b). The assembled transmission screen using the fabricated Gabor superlens and field lenses L₃ and L₄ is shown in Figure 3-14(d).

In our experiment, a 23 inch LCD screen with low diffraction, 60 Hz refresh rate and resolution of 1920×1080 is placed in front of the transmission screen without a gap makes it possible to display images that have more resolution. Speckle effect arises when coherent light scattered from a rough surface. This problem is common in laser projector system because the projection screen is a 2D diffuser and thus reduces the resolution of the perceived image by the viewer. We replace the polarizers of the LCD with shining polarizers to remove the scattering effects and also the speckle effects. The distance (D₁) between scanner and field lens L₁ is about 510 mm, the field lens L₁ to FLC-SLMs distance (D₂) is about 485 mm, and the FLC-SLMs to screen distance (D₃) is about 710 mm. The overall experimental setup is shown in Figure 3-15. Table 1 summarizes the detailed specifications of the

developed 3D display.

Figure 3-15 Experimental setup of the developed 3D display with scanning laser backlight.

Specifications		Values
LCD screen	Resolution	1920 X 1080
	Screen size	23 inch
	Refresh rate (Hz)	60
Laser	Wavelength (nm)	556
	Power (mW)	800
Scanner	Angle (°)	0 - 40
	Round trip time (μs)	100 - 200
FLC-SLM	Number of FLC-SLMs	8
	Pixel number per FLC-SLM	32
	Pixel width (mm)	1.17
	Pixel height (mm)	20
Field lens	Focal length of lens L ₁ (mm)	250
	Focal length of lens L ₂ (mm)	330
Elliptical diffuser	H-diffuser	10° × 2°
	V-diffuser	15° × 2°
transmission	Angular magnification	4

screen	Number of MLA layers	2
	Focal length of lens L ₃ (mm)	672
	Focal length of lens L ₄ (mm)	1000
	Total thickness (mm)	35
Viewing distance (mm)		1000
Field of view (°)		28.1

Table 3-1 Specifications of the 3D display using scanning laser backlight.

3.7 Experimental Results and Discussion

3.7.1 Measurement of Synchronized Signal Waveforms

Figure 3-16 Measurement of the signal waveforms among (a) VSYNC; (b) laser TTL signal; (c) scanner; (d) FLC-SLM and (e) frame signal.

The displayed images are synchronized with the laser, scanner and FLC-SLM. The signal waveforms among the VSYNC, laser, scanner, FLC-SLM and displayed

images are shown in Figure 3-16. The trigger signal from the video source is presented in Figure 3-16(a) and provides a 60Hz pulse for each frame. The laser transistor-transistor logic (TTL) signal is in charge of modulating the laser backlight and has a 60 Hz square waveform as shown in Figure 3-16(b). The laser is switched on at a high voltage waveform, while the laser is switched off when the FLC-SLM is direct current (DC) balance state. As shown in Figure 3-16(c), the scanner is driven by an analog sawtooth waveform. The scanner reaches the maximum rotating angle at the highest voltage, and then the scanner returns to origin during the DC balance period. It is quite obvious that the laser and scanner have the same periods of waveforms. As shown in Figure 3-16(d), the FLC-SLM is in the transparent state when the driven by a high voltage and in the dark state when driven by a low voltage. The FLC-SLM needs DC balance in order to give a zero cumulative value of voltage over one period. The duty cycle is set as 50 % when driven by ± 10 V. The waveforms shown in Figure 3-16(e) demonstrate the frame signal indicating the different views.

However, in practice, there is still a time consuming for the LCD to process the video data. Taking the synchronization inconsistency exists between VSYNC signal and displayed images into account, the delay time is measured and the same delay time period is inserted between the VSYNC and the trigger signal of each driver module in order to compensate for this latency introduced by the LCD. The FLC-SLM pattern would eventually synchronized with the video frame on LCD. In our prototype, the delay time is approximately 1.7 ms. In particular, the laser output should modulate during the refresh time of LCD aiming to remove undue crosstalk in the displayed images.

3.7.2 Crosstalk Analysis

Crosstalk is one of the critical defects affecting the image perception in autostereoscopic 3D displays. Generally, the ratio from the unexpected rays can be

used to quantify the 3D image quality, and the crosstalk ratio (CR) of the n^{th} view zone in N viewing zones case is defined as[33]:

$$CR_n = \frac{\sum_{j=1, j \neq n}^N \text{Light intensity}_{(j)}}{\sum_{j=1}^N \text{Light intensity}_{(j)}} \times 100\% \quad (3.19)$$

Lower value of the CR_n indicates better performance of the 3D display. Figure 3-17 shows left and right eye viewing zones, which were captured by a camera at the optimum viewing distance. The width of each eye viewing zone is about 31 mm, and the distance between two viewing zone centers is approximately 65 mm, which is identical with the average inter-pupillary distance (IPD).

Figure 3-17 Captured image of the left and right eye viewing zones at the optimal distance.

To quantify the level of crosstalk, we use a spectroradiometer to measure the light intensity. Figure 3-18(a) shows the normalized measured intensity distribution. The dashed line represents the viewing zone of left eye and solid line represents right eye. The both eye viewing zones are calculated according to Eq. (3.19). The calculated results are shown in Figure 3-18(b), which demonstrate the relation between CR and the viewing position in the horizontal direction. As shown in this

figure, the minimal crosstalk of both viewing zones is about 7.4% and 3.8%. If we want a good quality of 3D display, the crosstalk value should lower than 5% [34, 35]. The experiment result is acceptable in autostereoscopic 3D display.

Figure 3-18 (a) Normalized measured intensity distribution at the viewing zones; (b) calculated crosstalk of the viewing zones.

3.7.3 Real-time Eye-tracking Performance

Figure 3-19 Position of FLC-SLM aperture vs corresponding location of viewing zone.

To increase horizontal viewing freedom and implement motion parallax video, an eye-tracking technique is employed in the display system. The XYZ values

corresponding to the viewer's location are captured by the depth camera and the tracking data is transmitted to the workstation through a USB 3.0 port. The X and Y-coordinate values are transferred to the FPGA by the workstation via the USB port in real-time. Meanwhile, 3D video data is sent to FPGA through HDMI input port. The VSYNC signal from the input video stream is collected and then sent to LCD screen through HDMI output port. The other driver modules are triggered to operate when the VSYNC signal is collected.

The laser driver uses a digital buffer to generate a square digital waveform in order to modulate the laser output. The scanner driver using a digital to analog convertor that is driven by the FPGA which produces an analog sawtooth waveform that drives the scanner. Because the electrically addressed FLC-SLMs can only be driven by bipolar voltages, the SLM driver consists of a high voltage switch array driven by the FPGA which translates the digital waveform to ± 10 V bipolar waveform. In real time the FPGA generates the corresponding apertures of the FLC-SLM according to the tracking data from depth camera.

In Figure 3-19 the location of viewing zone is plotted as a function of aperture position at the FLC-SLM. The detected distance is 1000 mm for an optimal viewing distance. From Figure 3-19, it is worth noting that the position of the FLC-SLM aperture is linearly dependent on the corresponding location of viewing zone. The linear relationship indicates that the conjugated plane is well mapped with the FLC-SLM plane in the optics system. It facilitates the tracking algorithm when viewer is moving at the conjugate plane. The horizontal viewing range W_4 is about 500 mm at the detected distance D_4 , which is 1000 mm.

3.7.4 3D Image Effect and Motion Parallax

Figure 3-20 (a) Perspective and (b) top views of the solid images; (c) left and (d) right images to be displayed.

To evaluate the 3D imaging quality of our developed display system, we designed a football 3D model and two cube 3D models using Unity3D software. Figures 3-20(a) and 3-20(b) show the sides and the arrangement of these objects. These solid objects are away from each other in 150 mm depths to provide an impressive feel of depth. Figures 3-20(c) and 3-20(d) show the input images to be displayed. The letters “L” and “R” are added at the bottom of the corresponding left and right images aiming to identify the left and right views. It is demonstrated that reconstructed images have different views at the left and right side.

Figure 3-21 Photograph of left and right images at different viewpoints. The top row shows left view for a horizontal displacement of the user, and the lower a right view.

Figure 3-21 shows five different perspectives of the viewing images captured by a digital camera placed at -176 mm, -87 mm 0 mm, 87 mm and 176 mm, which

are corresponding to the source images at viewing angle from -10° , -5° , 0° , 5° and 10° . The left and right viewing images are shown in first and second row respectively, indicating a clear separation between left and right views. An overlap between neighboring objects occurs when the observer is located at different viewpoints, and the results indicate the motion parallax between the objects at the different depths is apparent. In addition, the corresponding movie shows the effect of the motion parallax when the user is moving between -10° and 10° at both sides of the axis.

3.8 Conclusions

A 3D display system that uses scanning laser source, addressed FLC-SLMs and transmission screen has been demonstrated. Using a high speed scanning backlight and high speed light switching FLC-SLMs, full-resolution and vivid 3D images are offered, which shows advantage compared with other display systems by employing directional backlight and time sequential methods. Moreover, by incorporating the eye tracking system within the 3D display, the viewing freedom is successfully extended without limiting the viewing position. The proposed method is expected to enhance the possibility of a laser-based 3D display as a 3D television.

4 Three-Dimensional Display using LED Directional Backlight

Backlight

4.1 Introduction

We proposed an autostereoscopic 3D display using a high-density LED-based directional backlight. This system consists of a set of cylindrical lenses lit by LED array, a linear Fresnel lens and a full-resolution LCD. The LED array controls the converging direction of the backlight, which projects left and right 3D images on viewer's eyes. The experimental results demonstrate a full-resolution 3D contents with natural 3D effect, high contrast ratio. This method has great potential in low-cost large autostereoscopic 3D display.

4.2 System overview

Figure 4-1 (a) System overview of the proposed 3D display using LED backlight; (b) cylindrical lens using spherical surface and polynomial surface.

As shown in Figure 4-1(a), the LED-based display system consists of cylindrical lenses, LED array modules, and a high definition panel. Figure 4-1(b) show the cylindrical lens structure, which has spherical back surface and odd polynomial front surface. The spherical back surface enables the LEDs to point at the soft aperture.

The odd polynomial surface converges the LED light to a bunch of collimated backlight. At the adjacent face of the two parts, black tape is attached to cover the unwanted area and lets the light pass through the central area, which is named soft aperture. The soft aperture is designed to block the unwanted LED light ray. The optical principle of the cylindrical lens is shown in Figure 4-2 as below.

Figure 4-2 Optical principle of the cylindrical lens.

These lenses are piled up in several layers as shown in Figure 4-3(a). At the back surface of the lenses, Customized LED array modules are mounted. The adjacent layers are displaced with certain pitch. Figure 4-3(b) shows the arrangement of the aperture of the lenses, which are carefully aligned. As shown in Figure 4-1(a), a field lens and a diffuser are placed behind the LCD screen. The field lens can converge LED light at the user's eye and the elliptical diffuser is aimed to unify the backlight.

Figure 4-3 (a) The cylindrical lenses arrangement; (b) soft apertures of lens in the front view.

The cylindrical lens can direct the light beam to the user. The displayed left or right image on the LCD is synchronized with the directional backlight. Because of vision persistence, viewers can watch 3D images in front of the screen without wearing glasses.

4.3 Principle of 3D Display using LED Directional Backlight

Figure 4-4 Principle of 3D display based on LED array.

As shown in Figure 4-4, assuming that the light source is positioned at the origin. The light ray transmits through the cylindrical lens, field lens and finally converge in the viewing zone. In the horizontal direction, the cylindrical lens focusses the light beam in narrow beam. In the vertical direction, the light beam is converged by the field lens.

Figure 4-5 Illustration of viewing zone formation of one cylindrical lens in the tangential plane.

Because the cylindrical lenses are fabricated with two parallel reflective sides, the reflections of the light source can form a set of virtual light sources as shown in Figure 4-5. The number of reflection is given by:

$$N = \text{floor} \left[\frac{1}{2} + \frac{d_1}{H} \tan \varphi \right] \quad (4.1)$$

where d_1 is the length of the lens, H is the height of the lens and φ is the half cone angle of the incident light. The field lens is a linear Fresnel lens, whose focal length are f . The grooves of the linear Fresnel lens are parallel with respect to the x axis in Figure 4-4. Therefore, the focal length of the field lens is described as follows:

$$\frac{1}{d_3} + \frac{1}{d_1 + d_2} = \frac{1}{f} \quad (4.2)$$

The viewing zone in the tangential plane is the magnified image of the virtual sources. The magnifications M is given by:

$$M = \frac{V_t}{N \times H} = \frac{d_3}{d_1 + d_2} \quad (4.3)$$

However, the V_t is a vertical line of spots. To make the vertical view uniformed, a vertical diffuser is placed at the output of every lens.

Figure 4-6 Illustration of viewing zone formation of one cylindrical lens in the sagittal plane.

The viewing zone formation of one cylindrical lens in the sagittal plane is shown in

Figure 4-6. E_s is the width of the exit pupil of the cylindrical lens. V_s the width of viewing zone. W_s is the width of the illuminated area of the LCD. In the sagittal plane, the linear field lens cannot bend rays. The exit rays from each LED would converge to a small zone. Therefore, the width of single LED decides the increments of the position of the viewing zone. The width of the viewing zone in horizontal is described as:

$$V_s = n_{LED} \times W_{LED} \times \frac{(d_2 + d_3)}{d_1} \quad (4.4)$$

where W_{LED} is the width of the LED, n_{LED} is the number of LEDs that are turned on. The width of the illuminated area of the LCD W_s is given by:

$$W_s = (E_s + V_s) \times \frac{d_3}{d_2 + d_3} \quad (4.5)$$

In order to cover the width of the LCD. The minimum number of the cylindrical lenses is:

$$n_{lens} = \frac{W_{LCD}}{W_s} \quad (4.6)$$

Figure 4-7 Principle of the steering backlight of one lens (a) backlight is converged on the right eye of viewer; (b) backlight is converged on the left eye of viewer.

Figure 4-7 shows the principle of the steering backlight of one lens. The linear

Fresnel lens doesn't affect the light beams in the horizontal direction. By controlling the illuminated LED pattern, the light beam goes through the soft aperture and converge on the left or right eyes of viewer.

4.4 Construction of Input 3D Image

Figure 4-8 Illustration of sequential view output method.

Unity3D[31] software is used to construct the images as shown in Figure 4-8. Two virtual cameras are assigned to capture objects. The images for left and right views are captured in sequence. Then, the two sets of captured images are interpolated together frame by frame. The gap between two virtual cameras is 60 mm, and the distance between cameras and objects is 1700 mm. In this display, a frame rate of 60 Hz for each eye is required, so the refreshing frequency of the 3D image is 120 Hz.

4.5 System Synchronization

Figure 4-9 Block diagram of steering backlight method.

The system block can be mainly divided into three modules as shown in Figure 4-9. Workstation, FPGA board and LED Backlight. The workstation is in charge of initializing and commutating with the FPGA board. The workstation interacts with the FPGA board through USB cable. In addition, it streams 3D time-sequential video to FPGA through HDMI cable. In the FPGA board, it consists of three modules to achieve the synchronization between LED backlight and the input 3D video. Firstly, the decoding module decodes the 3D video into frames and picks up the VSYNC signal, which contains the frame switching information and will be used to synchronize other modules. Then the 3D video will be encoded and exported to Monitor through HDMI cable. Secondly, the VSYNC signal is captured by the Synchronization module, a trigger signal will be generated after an appropriate time delay. The time delay intends to remove the phase difference between input video stream and the displayed video on monitor.

Secondly, the backlight pattern module generates the LED patterns according to the pupil position of viewer through optical calibration. When the sync signal triggers this module, the left and right patterns will switch in designed frequency. Based on the trigger signal, a modulation signal with a desired duty cycle is

generated to modulate the backlight, which can reduce the crosstalk between left and right views effectively.

Because there is overhead for the LCD to playback the video, phase difference exists between the captured VSYNC signal and displayed image on LCD. We insert a time delay module before the trigger signal to compensate the phase difference. In order to measure the exactly time delay needed, a test 3D video, which only consists of white and black frames and switches between these two frames, is playing on the system. Meanwhile, a laser beam is pointed at the screen and an optical detector is located on the other side of the screen to detect the laser beam, which represents the video frame switch.

4.6 Prototype Setup

Figure 4-10 Photograph of the proposed 3D display prototype .

Photograph of the established 3D display is shown in Figure 4-10. The prototype has 12 cylindrical lenses and LED array modules, which are stacked in 3 layers. Therefore, the backlight of the 42 inch LCD is divided into 12 vertical rectangular zones. These vertical zones are closely adjacent to generate a uniformed backlight. In general, more cylindrical lenses can achieve a brighter and more uniformed

backlight. However, more cylindrical lenses require more precise calibration of the lenses, otherwise the viewing zones of left and right eyes will be enlarged and thus increase the crosstalk if the viewing zones are overlapped.

Figure 4-11 Photograph of (a)customized LED array module; (b)ellipsoid diffuser; (c) Fresnel lens.

Figure 4-11 (a) shows customized LED array module. Each module has 32 LEDs. The adjacent LED pitch is 0.3 mm. The arc structure of the LED module matches the back surface of the cylindrical lens. To compensate the loss of intensity due to the long distance from the directional backlight to the LCD, we choose high power LED with small size so that more LEDs are enabled in single LED array module when left or right image is displayed. The single LED's luminous flux is 46 lm at 120 mA. It has a small dimension of 1.4 mm x 4 mm. Therefore a single module turns on as much as 5 LEDs and totally 60 LEDs are lit up for left or right view to ensure that the display can be watched under ambient lighting condition. As shown in Figure 4.11 (b), the diffusion angles of the elliptical diffusers are 10° in vertical and 2° in horizontal. The linear Fresnel lens is shown in Figure 4.11 (c). The detailed specifications of our developed system are listed in Table 4.1.

Specifications		Values
Display device	Resolution	1920 x 1080
	Screen size (diagonal)	42 inch
	Pixel size	235um×78 um
Elliptical diffuser	Distribute angle	10°× 2°
Fresnel lens	Focal length	1500mm
Cylindrical lens	Arrays	12
	Soft aperture	6mm
	Width	280 mm
	Length	411 mm
	Focus length	297 mm
LED	Size	1.4mm×4mm

Table 4-1 Specifications of the 3D display using LED backlight.

4.7 Experimental Results and Discussion

Figure 4-12 System timing of (a) frame signal (vsync), (b) measured test images and (c) enable signal of LED array.

Figure 4-12 shows the timing relationship of the frame signal, measured test images and enable signal of LED array. Figure 4-12(a) shows the sync signal, which represents the start of each frame. Figure 4-12(b) shows the displayed test images

for left and right views, each of which is 30 Hz. In Figure 4-12(c), the enable signal of LED array with low effective level is aligned to the displayed images. The duty cycle of the LED backlight is less than 50% to reduce the crosstalk ration. The experimental result shows excellent system synchronization.

Figure 4-13 Constructed input 3D images of (a) left view (b) right view.

Two 3D cube models are created to demonstrate the input 3D images, as shown in Figure 4-13. Figure 4-14 shows the photographs of the captured left and right views at two adjacent frames.

Figure 4-14 Photographs of the captured left and right views at two adjacent frames.

In the x axis, t_0 represent the time point when left view denoted as “View 1” is captured by high speed camera. Δt is the time period of one frame. At the time point $t_0 + \Delta t$, right view denoted as” View 2” is captured. The experimental result shows

a clear separation between view 1 and view 2 with minor cross-talk.

Figure 4-15 (a) Normalized measured intensity distribution at the viewing zones; (b) calculated crosstalk of the viewing zones.

Crosstalk is one of the critical defects affecting the image perception in autostereoscopic 3D displays. The crosstalk defined to express the effect between two views is given by:

$$C_n = \frac{I_n}{I_n + I_{n+1}} \times 100\% \quad (4.7)$$

I_n and I_{n+1} means the light intensity of two adjacent viewpoints. Lower value of C_n means higher performance of 3D display. We use a spectroradiometer to measure the light intensity of the left and right viewing zone. The normalized intensity is shown in Figure 4-15(a) and the calculated crosstalk is shown in Figure 4-15(b). The solid line represents the light intensity of right viewing zone and the dashed line represents the left viewing zone. The distance between left and right eyes is about 65 mm. calculating from Eq. 4.7, the crosstalk of right view and left view are about 19% and 14% respectively. The crosstalk is caused principally by the internal reflections and scattering at the surface of the optical components and air interfaces that exist in our current prototype. In our system, scattering is principally due to two factors: scattering at a diffuse antireflection surface on the polarizers and diffraction

at the LCD subpixels. In addition, the measured contrast ratio of the display is around 300:1. According to the measured results, a time-multiplex autostereoscopic display with low crosstalk is developed.

4.8 Conclusions

A time-sequential 3D display using a high-density LED-based directional backlight is proposed and demonstrated. The system uses a set of cylindrical lenses illuminated by LED array to converge the backlight on viewing zones of viewer's left and right eyes. By time-multiplexed technique, a full-resolution 3D images with natural 3D effect are obtained. Because it's easy to scale up the backlight with more cylindrical lenses, the proposed display has great potential in large size autostereoscopic 3D display.

5 Conclusion and Recommendations

5.1 Conclusion

In this thesis, two prototypes are proposed, established and demonstrated. The first prototype is an eye-tracked 3D display using modulated laser-based backlight, which consists of a scanning laser module, a ferroelectric liquid crystal spatial light modulator (FLC-SLM) array module, an assembled liquid crystal display (LCD) module. The scanning laser backlight is modulated by the FLC-SLM array to generate directional backlight. By means of eye tracking technology, the directional backlight is projected on the location of viewers' eye pupils in real time, which allows multi-viewers to move freely. A prototype system has been established to verify this idea. The experimental result shows that the fidelity of the 3D image is lossless with high brightness and contrast. The crosstalk of the 3D contents is below 5% which is acceptable. Viewers are enabled to move freely in a wide zone to watch 3D contents without wearing any glasses.

The second prototype is a time-sequential 3D display using a LED-based directional backlight. The system consists of a set of cylindrical lenses illuminated by LED array, linear Fresnel lens and high resolution LCD panel. A prototype has been established to verify the feasibility. The system is suitable for watching under ambient lighting condition and the full resolution 3D images with low crosstalk is obtained.

5.2 Recommendations for Further Research

5.2.1 Multi-user Eye-tracked 3D Display using RGB Laser Backlight and FLC-SLMs

The eye-tracked three-dimensional display based on laser backlight has

demonstrated the principle is feasible for single user. Further research can continue on this prototype.

Research on the fundamental mechanism of cross talk. Crosstalk reduction could be researched from several aspects. The pixel size of the SLM decides the smallest width of exit pupil. Smaller exit pupil can reduce the overlap area of the view zone of left and right eyes. Therefore, spatial light modulator with smaller pixels is one effective way to reduce crosstalk. LCD screen with small subpixel diffraction, high resolution and shining polarizers could reduce the diffraction effect and thus reduce the crosstalk. Optimization of system timing can also reduce the crosstalk. The system timing synchronization, for example the phase and duty cycle of laser backlight, can affect the view content, which is rendered line by line the LCD.

Research on RGB laser backlight with small beam diameter and beam divergence. The previous system employs a green laser which can only render monochrome image. RGB laser backlight is necessary for a better 3D experience. However, problem like different refractive indexes of red, green, blue lasers must be concerned.

Research on motion parallax 3D content. Due to the eye tracker, the displayed 3D content can be changed according to viewer's position. Viewer can choose the prefer viewing angle and get different view content.

Research on new optical system to reduce the system volume. The current prototype is very large. The design work should focus on the new optical components, smaller driver board and system integration. Small size can make this system be acceptable in television market and even for portable application.

Research on multi-user tracking and applications. Multi-user system is of great importance for 3D display. Currently the prototype can only support single user.

Multi-user system has higher requirement on the system bandwidth. Currently the fast LCD is 144 Hz in the market which can fulfill the demand of single user. High speed LED display which can reach thousand Hz are the solution for multiple viewers.

5.2.2 Eye-tracked 3D Display using LED Directional Backlight

The LED-based three-dimensional display has demonstrated that the principle is feasible for single user. In the next stage, further research will focus on this prototype.

Research on the fundamental mechanism of crosstalk. Crosstalk reduction could be researched from several aspects. For example: The LED width decides the minimum viewing zone for one eye. LCD screen with small subpixel diffraction, high resolution could reduce the diffraction effect and reduce the crosstalk; Optimization of system timing can also reduce the crosstalk.

Research on implement of eye tracker. Now the system can only be watched in fixed position. In the next stage, eye tracker will be integrated in the system, which requires wider LED array for large steering backlight. After the implement of eye tracker, research on motion parallax 3D content will be studied, which enables viewers to choose the prefer viewing angle and get different content.

Redesign the optical system to reduce the system volume. The current prototype is very large. In the next stage, new optical system should be designed to make the system slim.

Author's Publications

1. Zhuang, Zhenfeng, **Lei Zhang**, Phil Surman, Song Guo, Bin Cao, Yuanjin Zheng, and Xiao Wei Sun. "Directional view method for a time-sequential autostereoscopic display with full resolution." *Applied optics* 55, no. 28 (2016): 7847-7854.
2. Zhuang, Zhenfeng, Phil Surman, **Lei Zhang**, Rahul Rawat, Shizheng Wang, Yuanjin Zheng, and Xiao Wei Sun. "Moiré-reduction method for slanted lenticular based quasi-three-dimensional displays." *Optics Communications* 381 (2016): 314-322.
3. **Lei Zhang**, Phil Surman, Yuanjin Zheng. "Dynamic Head Tracked 3D Display Using Fast Spatial Light Modulator" *Photonics* 2017 @SG.

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