Different multi-focal-plane method

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12/08/2016

1. Introduction

Conventional stereoscopic displays render the depth perception of 3D scenes from pairs of 2D perspective images with binocular disparities presented on a flat screen at a fixed distance to the viewer. This type of displays creates a fundamentally different visual experience from our real-world viewing condition, thus forces an unnatural decoupling of the accommodation and convergence cues, which is known as the accommodation convergence discrepancy problem.

A multi-focal-plane display renders a series of 2D images at carefully placed, discrete focal distances, where each focal plane is responsible for rendering 3D objects within a depth range centered on it and these focal planes together render a volume of 3D space, which can minimize and eliminate the accommodation and convergence conflict. There are different methods to generate multiple focal plane display. They can be categorized into two types: spatial-multiplexing and time-multiplexing.

A spatial-multiplexed MFP display system spatially combines multiple 2D images sources. This method typically results in bulky system due to the duplication of display hardware which limits the implementation in head-mounted display.

A time-multiplexed MFP display system, the viewing distance of a single 2D display from the eye is rapidly switched in synchronization with the rendering of frames of multiple focal planes to create a flicker-free perception. Such method ultimately allows miniaturization of the system to be implemented in a compact AR head-mounted display. The main limitation of the time-multiplexed MFP display is the inability to generate enough number of focal planes at a flicker-free rate.

2. Existing Method

2.1. Thick Display

In a theoretical work by Rolland et al. in 2000, a method using a thick stack of transparent microdisplays was proposed [2]. The scheme of the system is shown as Fig.1. Based on a standard value of visual acuity of 1 arc min and a 4-mm pupil diameter, 14 focal planes are needed to cover the depth range from 0D to 2D.

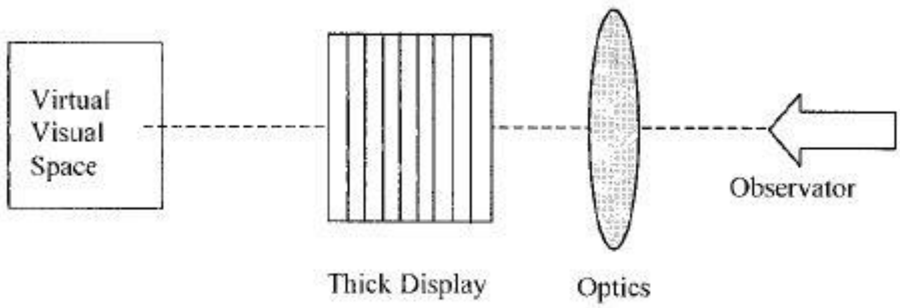


Figure 1

2.2. Fogscreen

In 2009, Cha Lee et al. demonstrated an immaterial two-focal plane room-sized 3D display using fogscreen [3]. They projected two images onto two fog planes which are configured in an L-shape as shown in Fig. 2.

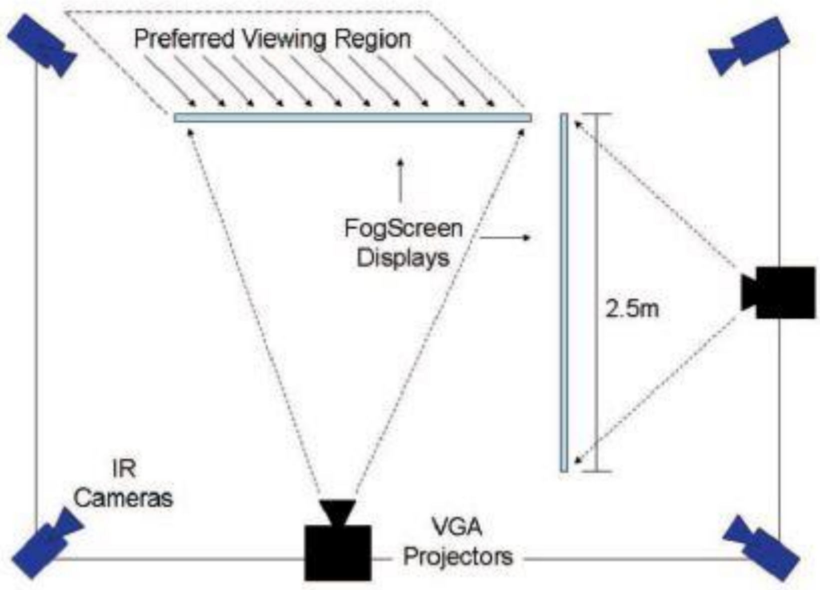
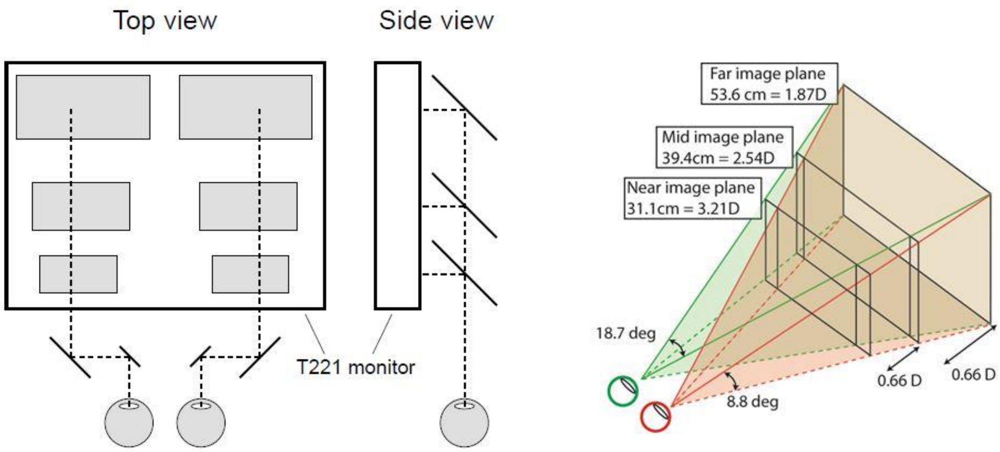


Figure 2

This system can hardly reach the 3D fidelity of stereoscopy because of registration errors and fog turbulence of the fogscreens.

2.3. Multiple Beamsplitter

In 2004, Kurt Akeley et al. demonstrated a three-focal plane display prototype by using beam splitters to generate a three-focal distances display [4]. No optical elements other than beam splitters and mirrors are used. Shown as Fig. 3(a), a LCD flat panel is viewed through plate beam splitters such that each eye sees three superimposed images. The positions of the beam splitters determined the distances of the images shown as Fig 3(b).



(a) (b)

Figure 3

The LCD flat panel that was used is IBM T221 LCD [2002]. Its horizontal and vertical pixel densities are both 80/cm. The flat panel dimensions are 0.478×0.299 m, with an overall resolution of 3840×2400 pixels. However, the use of a single flat panel limits the physical dimensions of the prototype display, and thus the available depth range and field of view.

Name	Distance	Diopters	ΔD	Spatial resolution
Near	0.311 m	3.21 D		1.38 arcmin
Mid	0.394 m	2.54 D	0.67 D	1.09 arcmin
Far	0.536 m	1.87 D	0.67 D	0.80 arcmin

Table 1: *Prototype image plane distances.*

The LCD flat panel is driven by a 128MB NVIDIA Quadro 900XGL graphics card, manufactured by PNY technologies [NVI2002]. The card has enough on-board memory to support the 9-Mpixel flat panel with 32-bit double-buffered color and a 24-bit Z-buffer, and to store the required texture images. Rendering performance is more than adequate, but because only two DVI display ports are available, the display frame rate is limited to 12 Hz at full 3840×2400 resolution. The low frame rate is acceptable because LCD flat panels do not flicker.

However, the performance of the devices has significantly improved these days. With the state-of-the-art devices, the performance of the prototype will be much better.

2.4. Electrically Focus Tunable Lenses

The latest Electrically Focus-Tunable Lenses from Optotune Inc. is 83-921. It has an aperture of 10.0mm and focus range from +45mm to +120mm. The response time is 2.5ms (10%-90% step).

2.5. Liquid-crystal (LC) varifocal lens

The focal length of the LC varifocal lens can be electrically varied by changing the effective refractive index of the LC region in Fig. 4.

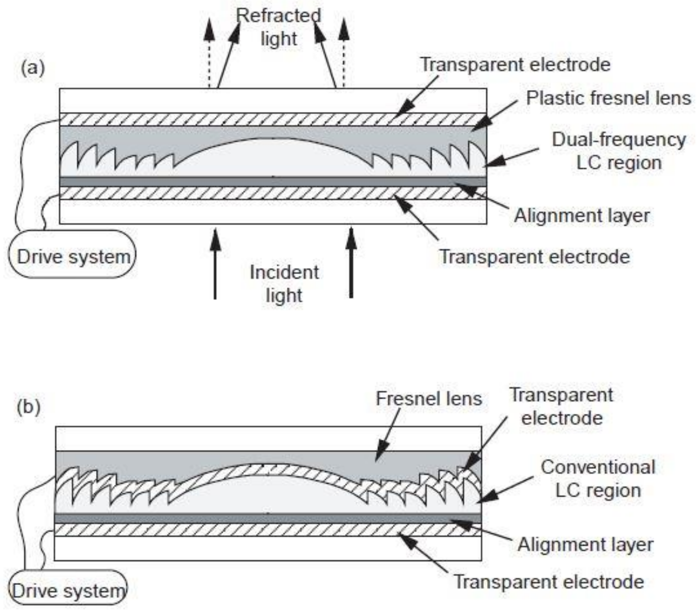


Figure 4

For a flicker-free 3-D display system, the LC varifocal lens must operate at a high speed of at least 60 Hz. However, a conventional varifocal lens [Fig. 5(b)] cannot operate over about 0.2 Hz. In order to increase the operating speed of that, Suyama et al. demonstrated a dual-focal-plane display using a dual-frequency liquid-crystal varifocal lens [5].This system can provide flicker-free, large 3-D images of 250mm in both diameter and depth with a viewing cone from -10 to +10 degrees. The focal length of the LC varifocal lens can be continuously varied from -1.2 to +1.5 diopters by changing the effective refractive index of LC. Using a dual-frequency LC for the varifocal lens achieves sufficiently fast operation of at least 60 Hz for flicker-free moving 3-D images. Figure 5(b) shows that the virtual images of the 2-D display can be easily shifted to arbitrary depth positions by changing the focal length of the LC varifocal lens. Thus,
The system can reposition the depth-sampled image by properly synchronizing the change of the 2-D image with the focal-length change.

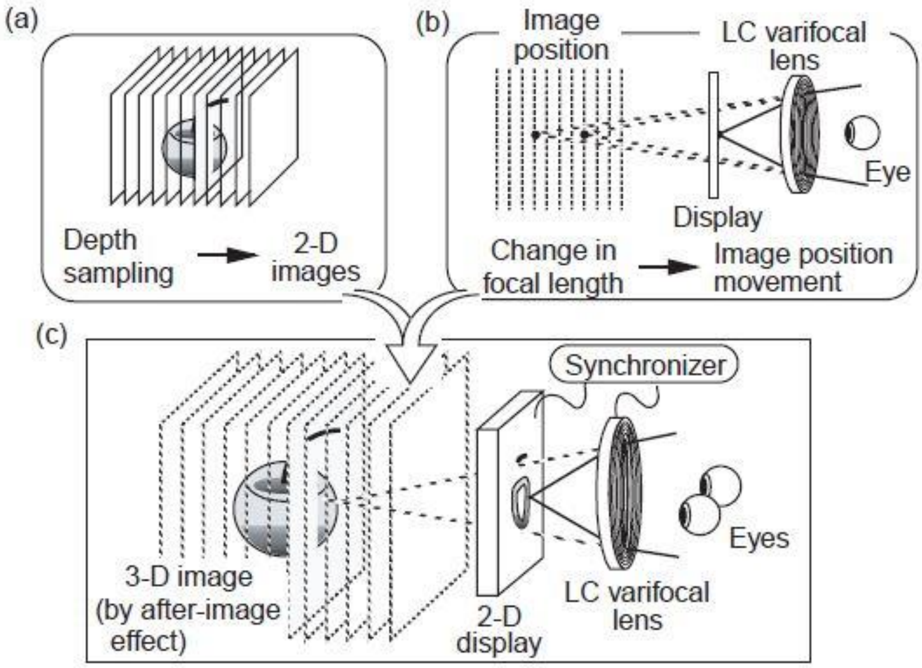


Figure 5

2.6. Liquid lens

Ming Kang and Ruifeng Yue presented a novel configuration of variable-focus liquid lens based on electro wetting-on-dielectric (EWOD) techniques, which is able to focus on objects away from 2.5 cm up to infinity with a good imaging quality [6].Jong-hyeon Chang et al. demonstrate a tunable liquid lens based on micro electro fluidic technology with an optical power range between 210D and −30 D [7].

Sheng Liu and Hua presented a dual-focal plane display prototype with addressable focal distances throughout a volumetric space from 8D to 0D enabled by a liquid lens device [8, 9]. They used the liquid lens (Arctic 314, Varioptic, Inc.), with a response speed of about 9 ms, to increase the frame rate of a dual-focal plane display to up to 37.5 Hz. They also compared the effects of two rendering mechanisms: The first method yields a higher refresh rate (e.g., f=37.5 Hz) and brighter image (B=1.0) but reduced image sharpness and focus cue accuracy, and the second method produces sharper images and more accurate focus cues but with compromised speed (e.g. f=18.75 Hz) and image brightness (B=0.5).

The latest liquid lens of Varioptic is Arctic 316. Focus range supports 5 cm to infinity Supports Continuous Autofocus for video up to 30 fps and fast response time (haven't found exact data).

2.7. Birefringent lens

Gordon D. Love et al. developed a four-focal-plane prototype with discrete addressable focal planes enabled by birefringence lenses [10]. The key technical innovation is the high-speed, switchable lens schematized in Fig. 6. The refracting element is a fixed birefringent lens. Birefringent materials have two refractive indices (ordinary and extraordinary) depending on the polarization of the incident light, so the lens has two focal lengths that are selected with a polarization modulator. If the lens is arranged such that the extraordinary axis is vertical and the ordinary axis is horizontal, incoming vertically polarized light is focused at a distance corresponding to the extraordinary refractive index.

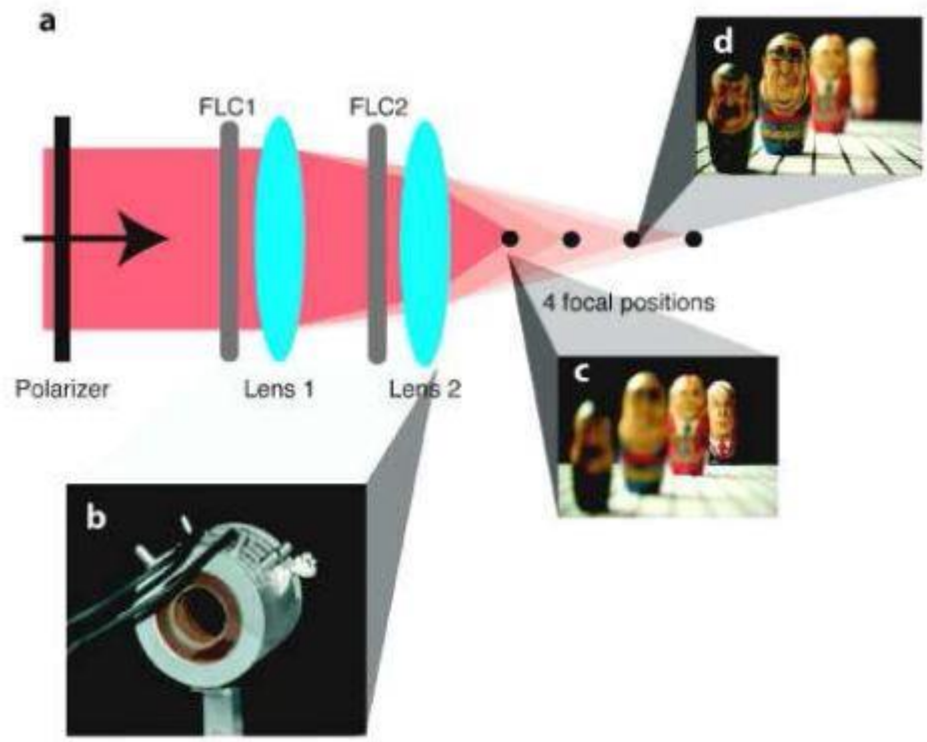


Figure 6

The first polarizer produces vertically polarized light that is then either rotated, or not, through 90° by the first ferroelectric liquid-crystal polarization (FLC1) switch. The first lens focuses the two polarization states differently. A second FLC and lens produces two more possible focal lengths for each of the first polarization states creating four focal states in all. The convex surfaces have radii of curvature of 143.3 and 286.7mm, so the four focal powers are 5.09, 5.69, 6.29, and 6.89 diopters (D), and the separations are 0.6D.

This system improves the refresh rate to about 45Hz for four focal planes, but the obtainable frame rate and the number of focal planes are limited by the bulky and slow CRT display used in the system, making it difficult to render a large depth range smoothly at flicker-free speed.

2.8. Wavefront coding

Xinda Hu and Hong Hua presented a relay lens groups using a deformable membrane mirror device (DMMD) and a digital micromirror device (DMD) to generate images for different distance [11].
The image generation subsystem (IGS), with detailed optical layout in Fig. 7, achieves the core function of generating the multi-focal-plane contents. It consists of a high-speed digital micromirror device (DMD) microdisplay by Texas Instruments, a deformable membrane mirror device (DMMD) and relay lens groups. The IGS is essentially a zoomed relay system based on an active optical element (the deformable mirror) whose optical power can be electronically controlled at a high speed as fast as 1 kHz.

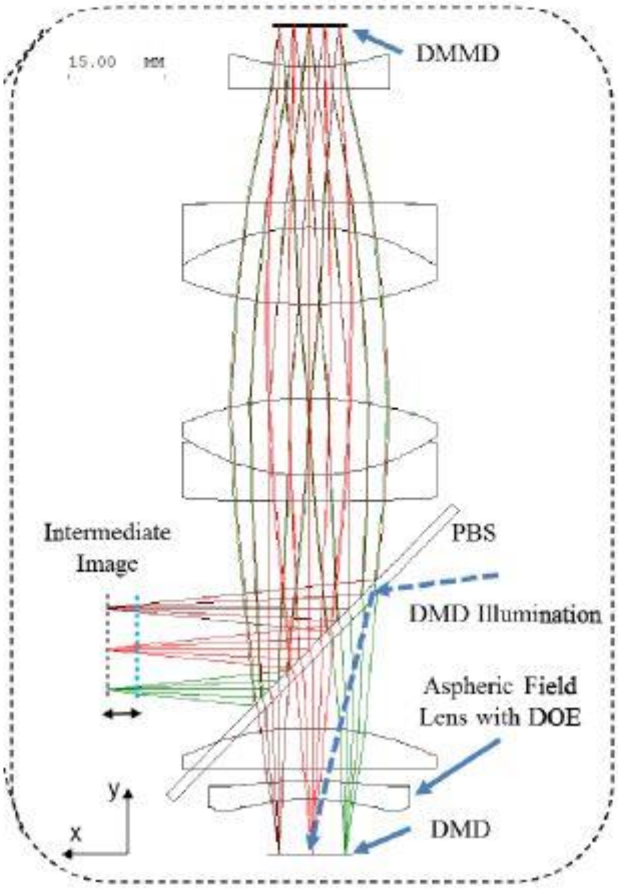


Figure 7

The prototype system is capable of rendering nearly-correct focus cues for a large volume of 3D space, extending into a depth range from 0 to 3diopters. The freeform optics, consisting of a freeform prism eyepiece and a freeform lens, demonstrates an angular resolution of 1.8 arc minutes across a 40-degree diagonal field of view in the virtual display path while providing a 0.5 arcminutes angular resolution to the see-through view.

Reference

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