Towards Direct-View Accommodative Light Field Displays

Graham J. Woodgate[1], Michael G. Robinson[2],Jonathan Harrold[1], Benjamin Ihas[2], Robert Ramsey[2]

[1]RealD Me, Magdalen Centre, Oxford Science Park, Oxford, UK

[2]RealD Me, 5700 Flatiron Parkway, Boulder, CO, USA

Abstract

Progress is reported on a programmable imaging backlight for a glasses-free light field display (LFD). Dynamic backlight steering combined with a micro-lens array is used to optimize image quality while reducing data loading with potential for compensating vision deficiencies. A resolution optimization analysis for micro-lens based LFD is provided.

Keywords

Augmented Reality; Light Field Display; Intelligent Backlight Technology; Autostereoscopic; Accommodation; Convergence; Presbyopia; Micro-Lens.

1. Introduction

Intelligent Backlight Technology (IBT), essentially a programmable light field display backlight, has been previously described[1], and uses an addressable linear array of LEDs at the input of an imaging directional light guide plate (D-LGP), and a micro-structured high brightness film (HBF) that together direct structured light fields through liquid crystal displays. By control of the illumination profile across the array of LEDs, the profile of the light fields can be adjusted, for example in tracking of moving observers.

Previously[2] the application and demonstration of IBT was presented for switchable privacy display, low stray light displays for night time operation and high luminance displays for outdoor use. Autostereoscopic (glasses-free) 3D demonstrations were also made that provide convergence depth cues.

A class of displays, referred to as "Light Field Displays (LFD)" that aim to deliver accommodative depth cues to users has been reported in recent years [3,4,5]. Much of this activity has been on headset platforms where independent imaging systems are allocated for each eye.

Here we report a unique capability of IBT-LFD technology – the potential for high resolution accommodative images in a Direct-View (no headset or eyewear), augmented reality (AR) display.

2. Light Field Display for Direct-View AR

2.1 Limitations of stereoscopic display

Much has been written regarding the conflict of accommodation and convergence in 3D displays[6]. In its cinema business, RealD is the world's leading provider of stereoscopic display technology with more than 2 billion people having experienced a movie in RealD 3D with convergence cues but no accommodation cues. In the authors' experience the visual stress issues reported with stereoscopic display are typically a result of failure to control one or more of the factors below to the same level as in Cinema:

3D image cross talk. With underlying display cross talk levels of around 1% combined with compositional sensitivity to presentation of high contrast edges, cross talk now has a low impact for the audience.

Vertical disparity between left and right eye images. The high quality of stereoscopic rendering tools now used by Hollywood has essentially eliminated this problem in the movie theatre environment.

Depth range selection. As with vertical disparity control, the movie industry has learnt to control depth ranges to known levels of visual comfort.

Percival's zone of comfort as illustrated schematically in Figure 1 may be used to predict the limits of comfortable depth representation in stereoscopic displays without creating visual stress from accommodation/vergence conflict. Note that cinema displays with images presented at several metres can provide wide depth ranges that are not accessible to handheld devices such as cell phones and tablets.

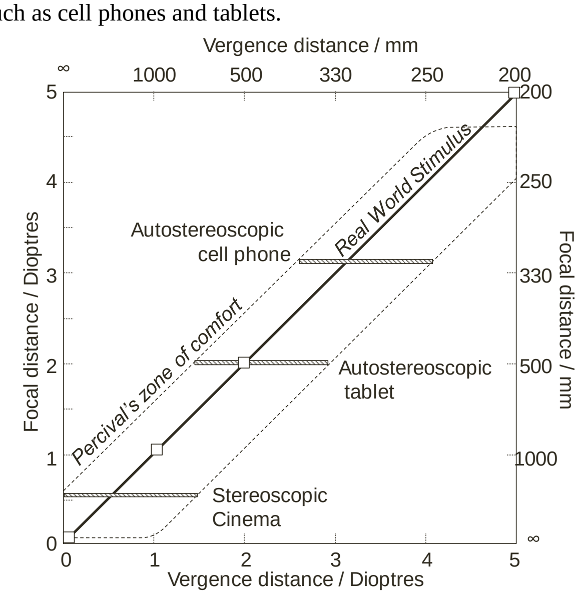

Figure 1. Comfortable depth ranges for various display viewing environments**.**

2.2 Direct-View Augmented Reality

Much previous AR display work has been based on semi-transparent headsets or glasses that superimpose computer generated information on the users view of the natural world.

In Direct-View AR, the added data is injected in registration with images from cameras, typically for viewing mobile displays such as cell phones and tablets.

However, overlaying Direct-View AR displays with the real world creates disconnects for both accommodation and convergence for the human visual system. For example, the focal distance of the display surface may be at 250~500mm distance while a typical real-world scene will typically be at several metres. Such differences demand accommodative adjustment between the data on the display and in the real world, and results in a loss of image registration between the two.

The overlap between real world and displayed imagery for Direct-View AR displays is illustrated in Figure 2.

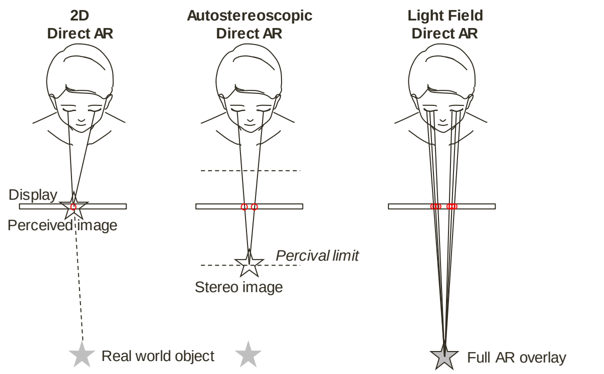

Figure 2. Projected images in autostereoscopic and light field AR systems extend image depth ranges for image overlay.

The mismatch of AR display distance to the real world may be somewhat mitigated using autostereoscopic display technology, providing visual cues that are closer to the real world than for 2D display. By directing different images to the left and right eyes of a user, convergence depth cues are provided which can more reliably match real world convergence cues. However, the user still has to focus on the display surface and comfortable depth ranges are constrained to the limits of the Percival zone of comfort.

As will be described below LFDs drive an accommodative visual process in each eye and offer the opportunity for focal (accommodation cues) and vergence (convergence cues) that lie on the real-world line in Figure 1.

2.3 LFD-AR for presbyopic correction

LFD-AR with accommodative capability also offers a future of spectacle free display for users with vision deficiencies such as presbyopia in which the visual system undergoes a loss of accommodative range. Figure 3 shows the impact on vision starts earlier in life than many are aware.

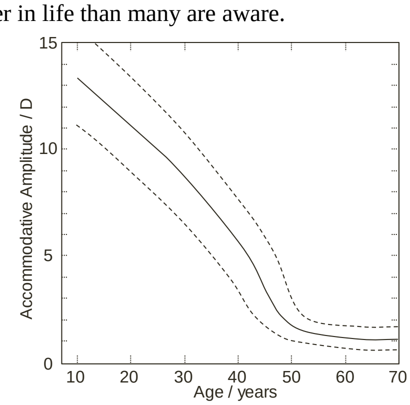

Figure 3. Effect of ageing on accommodative response for average users and distribution around average users[7].

The ability of the eye to effectively switch between near field images at the display surface and far field images in the real world in Direct-View AR may thus be impacted before the age users typically resort to reading spectacles.

3. Direct-View LFD operation

3.1 Micro-windows and visual feedback

The biomechanical processes of accommodation are illustrated in Figures 4 to 6, and are driven by the human visual system response.

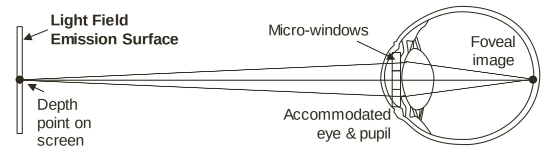

Figure 4. Accommodated eye and pupil for image point on LFD surface.

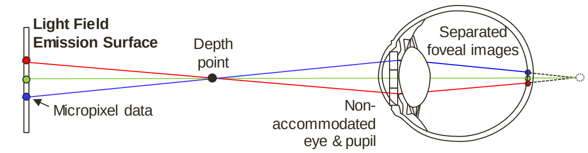

Figure 5. Adjustment of data sent to micro-windows creates multiple foveal images and causes image blur**.**

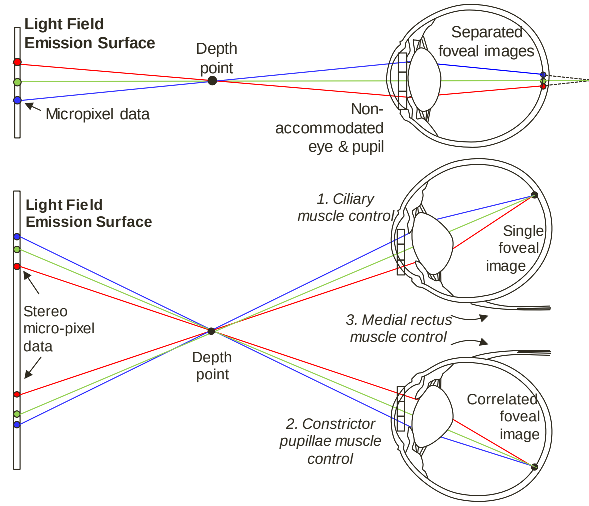

Figure 6. The visual cortex feeds back control to the muscles of the eyes to provide overlap of intra-pupil foveal images and correlated interocular foveal images, delivering sharp depth points away from the LFD surface.

The accommodative response of the eye is at least in part driven by a feedback system that adjusts lens shape to bring multiple light rays from the object that enter the pupil at different locations to a common focus. The human visual system also uses convergence cues to support the lens focus mechanism. Accommodative displays therefore need to reproduce these multiple ray bundles across each pupil of the user and maintain convergence cues.

3.2 Direct-View LFD implementation

3.2.1 Micro-lens based LFD

The significant challenge for LFDs is how to maintain image resolution and dynamic range, provide different views for each eye while providing multiple micro-windows within the pupil of each eye. Generating such high density micro-windows over a wide field of view in real time is (at the time of writing) prohibitively expensive both in the constraints of the physical display optical system and computationally.

LFD has much in common with autostereoscopic display, but with ray bundles that have an order of magnitude higher angular density, to produce an accommodative response. A potential approach to this can be envisioned using the spatial light modulator and aligned microlens array of Figure 7.

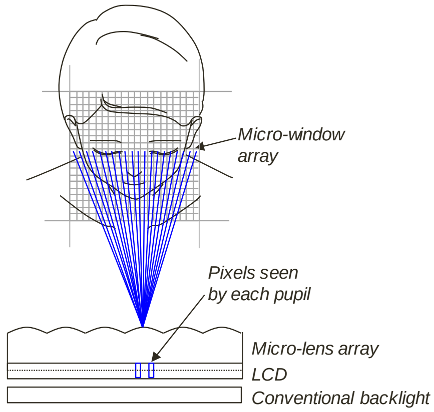

Figure 7. Conventional LFD structure

Such a display could be required to produce at least a 50x50 array of 2mm pitch micro-windows, which are then repeated in imaging lobes of the microlenses. Even with a pixel pitch of 10microns, such a lens would have only a 0.5mm x 0.5mm image resolution to produce such a vast number of independently controllable viewing windows.

3.2.2 IBT-LFD

A proposed optical stack to reduce the data loading challenges for Direct-View AR displays is illustrated in Figure 8.

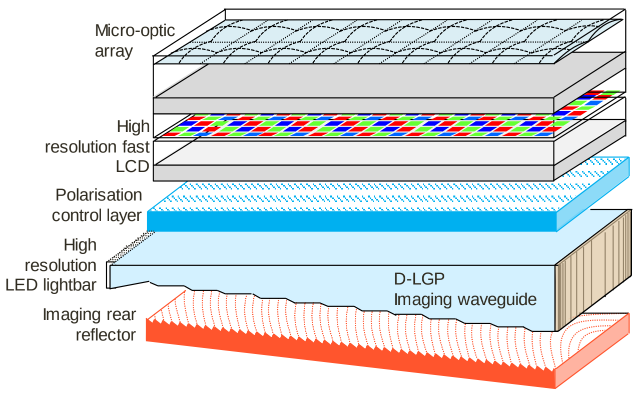

Figure 8. IBT-LFD structure combines a programmable imaging backlight and 120Hz LCD to deliver macro-windows while micro-windows are provided by a microlens array aligned to high resolution LCD pixels.

The unique high resolution macro-window generation optics of IBT can be leveraged to illuminate a spatially multiplexed LCD and provide time multiplexed bifocal Light Fields. As illustrated in Figure 9, time multiplexing of the LED array is synchronised with alternating images at corresponding macro-windows to the left and right eyes as in a conventional autostereoscopic display. A 2D microlens array is registered to the pixels on the LCD and creates an array of micro-windows at each of the user's respective pupils. Head and/or pupil tracking are used to adjust both the addressable LED profiles and the spatially multiplexed image data in response such that only the micro-windows that are illuminated by the macro-windows are visible to one of the user's eyes. The high redundancy of Figure 7 is eliminated, delivering substantially improved image resolution for a given underlying LCD pixel resolution.

A fully functional 10.1" autostereoscopic IBT demonstrator produces precise macro-window control as illustrated in Figure 10 with measured macro-window pitch of less than 10mm per addressed LED at a viewing distance of 500mm. Diffuser and LED lightbar design optimisation can be used to provide even finer levels of macro-window control and cross talk reduction.

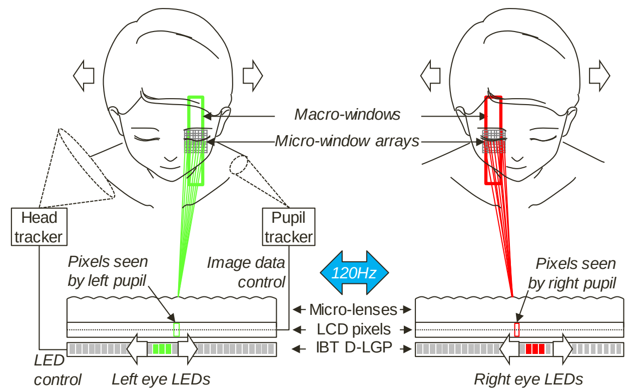

Figure 9. (Left) In the first illumination phase IBT delivers head tracked illumination of left eye micro windows that are generated by the microlenses & LCD with pixel data computed in correspondence with alignment to the pupil. (Right) In the second phase IBT delivers illumination to left eye macro-windows with overlaid micro-windows.

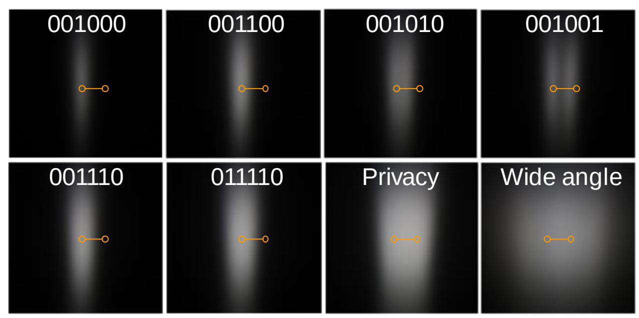

Figure 10. Photographs of IBT macro windows illuminating a white card at 500mm for various binary addressing patterns of the LED lightbar. Approximate left and right eye pupil locations are overlaid for each pattern.

3.3 Image resolution & microlens diffraction

Figure 11 illustrates the angular spreading associated with a single microlens producing a single ray from an accommodated image at infinity to an observer.

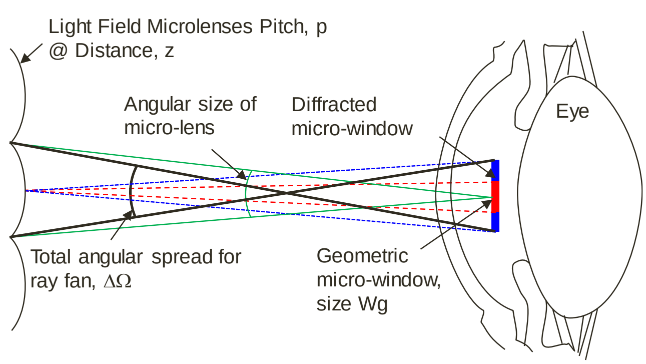

Figure 11. Resolution analysis for Direct-View LFDs for image relayed to infinity.

Equation 1 shows that the angular resolution of the display device for an image at infinite conjugate can be approximated from the RMS of the (i) the angular size of the microlens, (ii) the angular size of the geometric micro-window and (iii) diffractive spreading at wavelength, λ by the microlens of the geometric micro-window.

$$\Delta\Omega \sim \sqrt{\left(\frac{Wg}{z}\right)^2 + \left(\frac{p}{z}\right)^2 + \left(\frac{\lambda}{p}\right)^2} \qquad (1)$$

Considering other depth points, clearly if the accommodative image is in the plane of the display then the image resolution is limited by the microlens width Wg, independent of micro-window imaging properties. It can be shown that the achievable resolution ΔΩ scales with the accommodation distance, A as in

$$\Delta\Omega \sim \sqrt{\left(\frac{p}{z}\right)^2 + \left(1 - \frac{z}{A}\right)^2 \left(\left(\frac{Wg}{z}\right)^2 + \left(\frac{\lambda}{p}\right)^2\right)} \qquad (2)$$

Equation 2.

Figure 12 plots the variation of *Relative Visual Acuity*, that is the visual acuity as a proportion of 0.0003rad visual acuity (equivalent to 20/20 vision), against microlens pitch for a wavelength, λ of 550nm and illustrates the trade-off between diffractive spreading and micro-lens resolution for different micro-window widths.

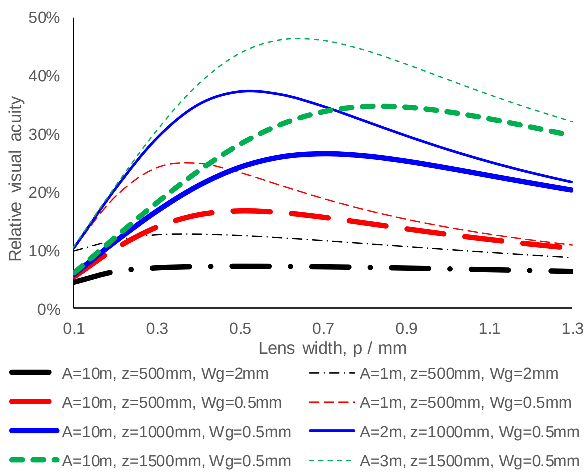

Figure 12. Variation of achievable image resolution against lens width for accommodation distance A, viewing distance z; and geometric micro-window size Wg.

Of particular interest to presbyopic users with limited visual acuity is the appearance of reduced resolution accommodative images in comparison to just increasing the size of images on their existing 2D displays, a comparison which is illustrated in Figure 13 for image pixels of equivalent angular resolutions.

The inability of the eye to focus on the display surface degrades the image blur B_d in comparison to the image blur B_a that arises due to the resolution loss ΔΩ. The accommodative LFD benefit is thus greater than that of just reducing 2D image resolution.

Further simulations will investigate details of phase propagation from microlenses to the retina, including the effects of apodisation and resolution enhancement. The visual appearance to real observers also requires characterisation.

The authors believe that new LFD-AR applications will emerge that leverage the ability of these displays to overlay real world images accurately with augmented data in usage cases where eliminating visual fatigue and managing presbyopia enable new paradigms for display.

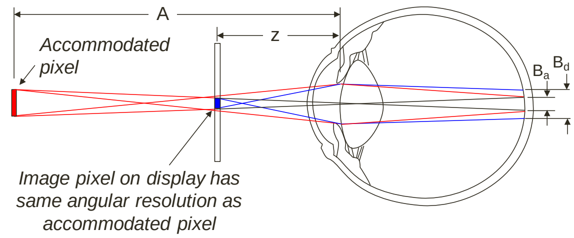

Figure 13. Raytrace illustrating variation of achievable image resolution B_a, B_d for accommodation distance A, viewing distance z; and geometric micro-window size Wg.

4. Conclusion

A novel Direct-View Light Field Display system capable of providing accommodation and convergence cues has been described. Intelligent Backlight Technology used to illuminate a spatially multiplexed LCD and aligned array of micro-lenses can supply high fidelity light fields to each eye. Such a display mitigates the redundancy of conventional micro-lens based light field display and compresses data pipelines.

A first order diffractive blur analysis has been made to investigate limits of resolution for accommodative images and point to future research directions. This analysis is relevant to all types of micro-lens AR displays including head mounted configurations.

IBT-LFD offers a roadmap for future fully accommodative images for Direct AR display and visual defect correction including presbyopia.

5. References

[1] M.Robinson, G.Woodgate, J.Harrold "Intelligent Backlight: A controllable illumination system for high efficiency and sunlight readable mobile displays", SID Digest 2014, Volume 45, Issue 1, pages 842–845, June 2014.

[2] Woodgate Graham J., Robinson Michael G., Sommerlade Eric, Harrold Jonathan, Ihas Benjamin and Ramsey Robert, (2015), P-162L: Late-News Poster: Intelligent Backlight Technology Developments for Uniformity, Privacy & 3D Operation, SID Symposium Digest of Technical Papers, 46, doi: 10.1002/sdtp.10009.

[3] Azuma, Ronald T. "Making Augmented Reality a Reality". Proceedings of OSA Imaging and Applied Optics Congress,San Francisco, CA, 25-29 June 2017.

[4] Fu-Chung Huang, Gordon Wetzstein, Brian A. Barsky, and Ramesh Raskar. "Eyeglasses-free Display: Towards Correcting Visual Aberrations with Computational Light Field Displays" ACM Transaction on Graphics, Aug. 2014.

[5] Douglas Lanman, David Luebke, "Near-Eye Light Field Displays ", ACM Transactions on Graphics (TOG), Volume 32 Issue 6, November 2013 (Proceedings of SIGGRAPH Asia).

[6] David M. Hoffman; Ahna R. Girshick; Kurt Akeley; Martin S. Banks "Vergence–accommodation conflicts hinder visual performance and cause visual fatigue" Journal of Vision March 2008, Vol.8, 33. doi:10.1167/8.3.33.

[7] Duane A. "Normal values of the accommodation at all ages" J Am Med Assoc 1912; 59: 1010-3.

