14.1: Resolution Artefacts in Multi-View Autostereoscopic 2D/3D Displays

Graham J. Woodgate, Jonathan Harrold

Ocuity Limited, 77 Heyford Park, Upper Heyford, Oxfordshire OX25 5HD, U.K.

Abstract

Autostereoscopic displays suitable for the mass market typically rely on spatial multiplexing to present different views in different directions. To obtain the wide viewing freedom often requested by display users, the number of views presented is increased by the sacrifice of display resolution.

In order to compare such multi-view displays, both quantitative and qualitative comparisons have been made of resolution losses and pixel appearance. Specifically, 2.2" 2D/3D panel performance has been assessed using Nyquist boundaries, human visual contrast sensitivity models and autostereoscopic display optical output simulations.

A strong candidate for an optimum compromise between display brightness, viewing angle and 3D pixel appearance is a 4-view vertical Polarisation Activated Microlens technology with either QVGA mosaic or VGA stripe pixel arrangements.

1. Introduction

Mass market autostereoscopic displays need to preserve base panel 2D image performance while meeting additional 3D image quality specifications. 2D image quality is generally delivered using switchable optical systems^[1,2,3,4], although non-switchable technologies have also been considered using high resolution LCDs^[5]. In the 3D mode of operation, image quality can be defined by quantifying viewing angle, image cross talk, pixel resolution, and pixel appearance.

The sampling losses for different 7-view displays have previously been compared and demonstrations made of displays with 18 and 32 separate views^[6]. Such displays offer a wide viewing freedom with relatively smooth switching between adjacent views, but exhibit substantial resolution losses and image cross-talk. As will be shown below, the artefacts associated with resolution losses in these systems are reported as very visible by display users.

Previous work by the authors^[7] examined the trade-offs in display window design, providing cross-talk and viewing freedom comparisons, which showed that vertical lens 4-view displays demonstrate superior cross-talk performance (providing increased comfort for viewing images with useful depth ranges) to tilted lens 9-view displays, with similar viewing freedom.

In this paper, the trade-offs in image appearance are compared for low view-density multi-view displays, considering frequency space analysis and human contrast sensitivity functions. Various multi-view display systems have been analytically and physically simulated and an initial analysis presented.

2. Display sampling

The 3D mode of a spatially multiplexed display has reduced resolution. To assess optimum design parameters, it is necessary to investigate both the loss of resolution and the redistribution of the colour filter pattern in the 3D mode. The quantitative analysis of frequency structure using Nyquist boundaries is a well known technique for analysing the two dimensional distribution of sampling data points^[8,9].

The panel matrix array function $a(x,y)$ is the convolution of a two-dimensional comb function $\text{comb}(x,y)$, comprising a two dimensional δ function array, and a single pixel structure $\phi(x,y)$

$$a(x,y) = \text{comb}(x,y) \otimes \phi(x,y) \quad (1)$$

$$\text{comb}(x,y) = \sum_{i,j=-\infty}^{\infty} \delta(x-i\alpha, y-j\beta) \quad (2)$$

α and β are the horizontal and vertical pixel pitches, where typically for stripe configuration panels, $\alpha=\beta/3$. The reciprocal function (i.e. frequency spectrum) is thus given by:

$$A(\mu,\nu) = \text{comb}(\mu,\nu) \cdot \Phi(\mu,\nu) \quad (3)$$

where $A(\mu,\nu)$, $\Phi(\mu,\nu)$ and $\text{comb}(\mu,\nu)$ are the two dimensional Fourier transforms of functions $a(x,y)$, $\phi(x,y)$ and $\text{comb}(x,y)$. The green pixel matrix is used for reciprocal space analysis.

Multi-view displays can be categorized as: vertical lens displays with vertical or horizontal pixel columns^[1] (Figs.1a & 1b); vertical lens displays with mosaic pixel structure (Fig.2); tilted lens displays with vertical pixel columns^[2] (Fig.3); and step-barrier displays with vertical pixel columns, and a chequer-board barrier structure^[10] (Fig.4).

Fig.1a Vertical stripe panel, vertical lenses

Fig.1b Horizontal stripe panel, vertical lenses

Fig.2 Mosaic panel, vertical lenses

Fig.3 Stripe panel, tilted lenses

Fig.4 Stripe panel, step-barrier

In each case, the lattice points mark the position of green pixels. A comparison of sampling performance can be made by comparing reciprocal space lattice points, as shown in Fig.5.

Fig.5 Reciprocal space comparison for multi-view displays

This analysis can be used to determine the relative size of the Nyquist boundaries for different design approaches, as shown in Fig.6. For each of the 2D and 3D pixel structures, the boundary encapsulates frequencies that can be effectively sampled. For multi-view 3D displays, there is a reduction in the resolution in each view ($1/4$ for 4-view systems, typically $1/7$ to $1/9$ for tilted lens systems), which results in a reduction in the frequency space gamut.

Fig.6 Comparison sketch of Nyquist boundaries

3. Human Visual System response

3.1 Sampling limitations

The human visual system response to a frequency stimulus is complex, with influencing factors including lighting conditions, angle of dominant frequency stimulus, chromaticity and stereo depth cues.

A rigorous analysis of the human response function is beyond the scope of the present work and a circularly symmetric visual acuity function has been assumed. The reciprocal space radius of this function is set to be $0.5/\beta$, the width of the 2D stripe panel Nyquist boundary. If the reciprocal space gamut includes points which exceed the visual acuity function in a particular direction, then the panel is adequately sampling in that direction.

Below, the nature of the visual appearance of the under-sampling artefacts is examined in more detail.

3.2 Image artefacts

In 3D multi-view displays, two main artefacts arise from reduced resolution:

- Block artefact

As the Nyquist boundary shrinks, and the pixels grow in size, they appear more 'blocky' which can produce serrated edge image artefacts as shown for example in Fig.7.

Fig.7 Generation of image blockiness by resolution loss

The Nyquist boundary for the 9-view tilted lens system is relatively symmetric. However, the 4-view vertical lens displays have more than twice the boundary area, with much reduced block artefact. 4-view mosaic pixels show the best compromise between minimising reduction loss and symmetry of the Nyquist boundary for a particular panel resolution.

- Stripe artefact

The visual luminance response can be strongly affected by luminance differences between green and red/blue channels. As the separation of separate red, green and blue colour sub-pixels in the 3D mode increases and thus the colour sub-pixel spatial frequency reduces, the photopic response of the eye starts to resolve the individual colour sub-pixels with green (bright) stripes separated by blue and red (dark) gaps. The resultant luminance function is referred to as the *chromatic stripe artefact*. This artefact appears as dark stripes superimposed over the image data.

One model for the human contrast sensitivity function for lateral frequency structures ($\mu > 0, \nu = 0$) is shown in Fig.8^[11] for a 2.2" QVGA (320 x 240RGB) stripe panel viewed from 350mm.

Fig.8 Visual acuity model after Manos and Sakrison 1974

This model can be used to compare the contrast sensitivity of the eye to different 3D mode pixel arrangements, for a one-dimensional colour sub-pixel frequency pattern.

- The 4-view vertical stripe panel (Fig.1a) has a high contrast sensitivity and thus a clearly visible chromatic stripe artefact.
- For a 4-view horizontal stripe panel (Fig.1b), the colour sub-pixel spatial frequency is the same as for the base panel, and so the chromatic stripe artefact will not be visible.
- The lateral frequency gamut for the 4-view mosaic 3D pixel (Fig.2) is almost 3 times that of the equivalent vertical stripe panel, with minimal chromatic stripe artefact. At an inclined angle, the colour sub-pixel spatial frequency falls, increasing contrast sensitivity. In the simulations below, this produced a just-visible chromatic stripe artefact.
- The pixel arrangement of tilted lens displays (Fig.3) reduces the visibility of the chromatic stripe artefact, to a level similar to the mosaic panel.
- In step-barrier displays (Fig.4), a high contrast luminance function is introduced by the barrier structure. At the spatial frequencies of these elements, *amplitude stripe artefacts* may also be observed, arising from the barrier itself.

3.3 MTF & Cross Talk

The MTF (Modulation Transfer Function) of a display is the spatial frequency at which the contrast drops below a threshold value, for example 50%. However, cross talk between adjacent views degrades the contrast achievable by a pixel and thus the MTF response.

Displays with high levels of cross-talk thus degrade the MTF of the display in regions of high disparity beyond that shown by the Nyquist boundary analysis. Stereo cross talk artefacts further introduce visual strain to users in the 3D mode, or result in reduction of useful depth that can be presented by a display.

4. Multi-view display simulation

4.1 Pixel plane simulation

To provide equivalent comparisons between different display systems, an optical transparency simulation of LCD colour filters has been prepared. A sequence of up to 9 views based on the 'Picnic' image was produced using HumanEyes' Lite

Program^[12] which enables the depth range and zero disparity points to be set for real-world images. Images were processed to form equivalent pixelated image arrays on a nominal pixel lattice of 50x150 μ m. Image pixels were then written by red, green and blue laser scanner onto panchromatic photographic film, with a 12.5 μ m addressability.

Typical pixel appearances are shown in Fig.9. The limited addressability and spot sizes of the laser scanner means that it was not possible to produce a 'perfect' reproduction of the pixel aperture function $\phi(x,y)$. However, this does not affect the reciprocal lattice constants, so that the final results are representative of the visual appearance of a real display.

Fig.9 Film appearance for mosaic & stripe pixels

4.2 Autostereoscopic image simulations

Autostereoscopic transparencies were fabricated using Polarisation Activated Microlens^{TM[1]} structures as shown in Fig.10 and mounted above each other with common lateral window alignment, as shown in Fig.11.

Fig.10 Optical arrangement

Fig.11 Simulation lightbox

The use of a transparency with similar absorption losses to LCD colour filters, an LCD backlight, and polariser components results in system losses representative of a TN-LCD, providing realistic device simulation and comparison conditions.

4.3 Single view image simulations

Single view transparencies viewed without additional optics were also produced to simulate the resolution loss in just one of the 3D views, as shown in Fig.12. These allowed stereo image artefacts and optical cross-talk effects to be removed from observations of resolution artefacts.

Fig.12 Pixel structures for single view simulations

5. Observations

A 2.2" QVGA (320x240RGB) TFT-LCD was used to fabricate a horizontal stripe, vertical lens, 2-view switchable 2D/3D display using Polarisation Activated Microlens technology. This display was compared with the autostereoscopic transparencies with a very good visual match obtained. The single view transparency simulations also showed a good match to the appearance of a single image of the autostereoscopic transparencies, indicating that 3D pixel appearance is dominated by sampling effects.

The observed artefacts in transparency images were subjectively ranked as shown in Table 1 by four experienced 3D display users. Table 2 provides a comparison between the various 3D pixel simulations for a 2.2" QVGA multi-view image.

Table 1. Subjective ranking scores

Artefact ranking	Subjective appearance
4	No visibility
3	Just visible artefact
2	Clearly visible artefact
1	Very visible artefact

Table 2. Qualitative ranking of resolution artefacts

#views	CF ¹	Optic	Block	Stripe
2	HS	Vertical lenticular	3	4
4	VS	Vertical lenticular	2	1
4	M	Vertical lenticular	2	3
9	VS	Tilted lenticular	1	3
4	VS	Barrier	2	1
4	VS	Step Barrier ²	2	2

¹Colour Filter HS: Horizontal stripe VS: Vertical stripe M: Mosaic

²Single view image only

The best image quality was given by the 2-view horizontal stripe lenticular configurations. A 2.2" VGA (640x480RGB) in a 4-view horizontal stripe configuration provides high image resolution, minimal block artefact, no stripe artefact and multi-view operation. Further, mosaic colour filters are not used, and the nominal autostereoscopic viewing distance is minimised.

Of the wide viewing freedom 2.2" QVGA options, the authors concluded that the 4-view mosaic vertical lens configuration gave the best frequency response, showing minimal chromatic stripe and block artefacts. The superior cross-talk performance of this display in its sweet spots also allowed the MTF to be maintained compared to competing approaches.

6. Conclusion

The design of wide viewing freedom spatially multiplexed autostereoscopic displays requires careful consideration of trade-offs. The resolution artefacts present in different autostereoscopic display systems have been evaluated, and physical simulations constructed in order to qualitatively evaluate the relative performance of the technologies.

From an analysis of frequency sampling, human visual response models and simulation results, the authors have shown that tilted lenses overcome stripe artefacts but demonstrate high levels of resolution loss leading to very visible block artefacts, as well as creating high cross-talk.

For 2.2" 2D/3D panels, 4-view VGA horizontal stripe and 4-view QVGA mosaic pixel systems with Polarisation Activated Microlens technology are strong candidates for an optimum compromise between display brightness, viewing angle and 3D pixel appearance

7. References

- [1] J. Harrold, D.Wilkes, G.J.Woodgate "Switchable 2D/3D Display – Solid Phase Liquid Crystal Microlens Array", Proc. IDW, Vol.11, pp1495-1496, 2004.
- [2] S.T. de Zwart et al. "A 20" Switchable Auto-Stereoscopic 2D/3D Display" Proc. IDW, Vol.11, pp1459-1460, 2004.
- [3] H. Isono et al. Japanese Pat. Appln. JP03-119889, 1991.
- [4] R.R. Moseley et al., European Pat. Appln. EP0829744, 1997.
- [5] S. Uehara et al. "470 x 235ppi poly-Si TFT LCD for High-Resolution 2D and 3D Autostereoscopic Display" Asia Display/IMD04, 2004
- [6] K.Taira et al. "Autostereoscopic liquid crystal display using mosaic color pixel arrangement" Proc.SPIE vol.5664 pp349-359, 2005
- [7] G.J.Woodgate, J.Harrold "Key design issues for autostereoscopic 2D/3D displays" Eurodisplay05 pp.24-27, 2005
- [8] L.-M. Chen et al "Influence of pixel-structure noise on image resolution and color for matrix display devices", JSID 1/1, pp103-110,1993
- [9] Z.-I. Hara et al. "Improvement in the picture quality of moving pictures for matrix displays", JSID 8/2, pp129-137, 2000
- [10] Sanyo Electric Co., Ltd. "Step barrier system multi-view 3-D display without special glasses", Product flyer, 2003
- [11] J.L. Manos and D.J. Sakrison, "The effects of a visual fidelity criterion on the encoding of images," IEEE Trans. on. Information Theory, pp. 525–536, 1974
- [12] www.humaneyes.com