Multi-Viewer Autostereoscopic Display with Dynamically-addressable Holographic Backlight

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Abstract

An autostereoscopic display system, which allowed multiple viewers simultaneously by use of head-tracking, was previously demonstrated for TV applications in the ATTEST project. However, the requirement for a dynamically addressable, movable backlight presented several problems for the illumination source. In this paper, the authors demonstrate how the use of a novel laser-based holographic projection system can be used to address these problems.

1. Introduction

Three-dimensional (3D) displays, and their enabling technologies, are rapidly approaching the maturity required to become commercial reality. Perhaps the most familiar type of 3D display is stereoscopic, a relatively simple solution to the provision of 3D imagery which requires the viewer to wear special glasses. Anecdotal evidence suggests, however, that a strong preference exists for glasses-free (autostereoscopic) displays.

There are various approaches which can be taken to realise an autostereoscopic display. Holography clearly has the potential to provide the most realistic 3D display, providing true 3D with full parallax. Whilst 2D holographic projection displays are close to commercialisation [1],[2], 3D holographic displays are currently limited by the large amount of information that must be transferred and displayed. Although progress has been in made in relaxing the demands imposed by holographic 3D display technology by effectively exchanging spatial for temporal bandwidth [3], holography is unlikely to provide a mass-market 3D display solution for some years to come.

Volumetric displays, in which images are formed within a well-defined volume of space, are capable of providing autostereoscopic images although the hardware tends to be complex and currently provides only translucent images. Similarly, multi-view displays, in which a series of static image views are presented across the viewing field, provide a relatively simple and effective solution but suffer from having relatively restricted viewing regions, loss of resolution and limited depth of field.

The problems outlined above can potentially be addressed by a next-generation 3D display in which aspects of multi-view technology are incorporated, employing head position tracking to generate movable image views that may supply 3D to several viewers. This approach would enable a 3D display to present the minimum amount of display information, namely a simple stereo pair, with the minimum loss of resolution. With advances in display resolution and/or response time, such an approach would also have the potential to provide motion parallax.

To investigate such a next-generation 3D display technology, the European Union funded Multi-User 3D Television Display (MUTED) project (IST-5-034099) commenced in July 2006. It brings together seven participants from across Europe and over thirty person-years of effort. The philosophy of the MUTED project is to provide three-dimensional television (3DTV) by display of autostereoscopic imagery to multiple viewers, each of whom should enjoy freedom of movement.

The core concept of any multi-viewer display is to produce image regions (or exit pupils) in a space in front of the screen at the viewer's eye positions. Figure 1 illustrates this concept, in which an exit pupil is formed with the use of a large lens and a vertical light source. To enable viewer mobility, a head-tracking approach is employed to provide viewer positional information to the illumination source; variation of the position of the illumination source then causes a corresponding change in the position of the exit pupil.

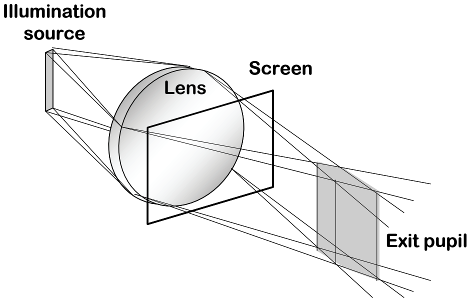

Figure 1 – Exit pupil formation using a lens and illumination source.

In order for 3D to be observed, two adjacent exit pupils per viewer must be formed. This can be achieved by placing a second illumination source adjacent to the existing source, thereby forming an additional exit pupil.

The task of providing multiple exit pupils is exacerbated by the presence of multiple viewers, each of whom should have unrestricted movement around a defined zone. It has long been recognised that a steerable backlight would be advantageous for forming dynamically changing exit pupils [4]; unfortunately, such backlights have proven very difficult to implement and have typically exhibited low efficiency [5].

The MUTED system demonstrates significant advances in the realisation of a multi-user autostereoscopic display, partly due to the provision of a dynamic laser backlight that simultaneously exhibits small form factor and high efficiency. The relative position of such a display in the head-tracked 3D display taxonomy is shown in Figure 2.

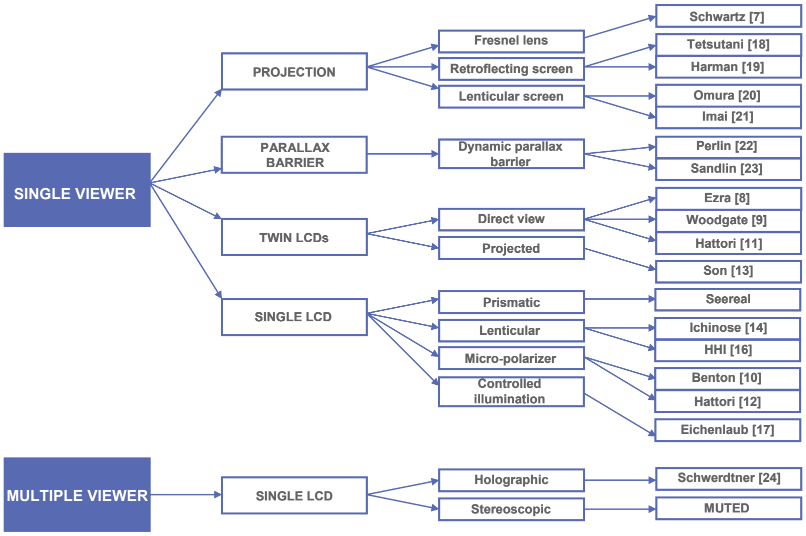

Figure 2 – Head-tracked displays taxonomy. The MUTED technology provides a multi-viewer, autostereoscopic display.

2. Steerable backlights for 3D displays

The shortcomings of dynamic steerable backlights were highlighted in the ATTEST [6] project, in which multi-user autostereoscopic image display was achieved by employing a liquid crystal display (LCD) showing interlaced left and right eye images on alternate pixel rows. A lenticular screen, placed behind the LCD panel, was used to focus a steerable backlight through the left and right image rows of the LCD. Crucially, steering of the viewpoint was accomplished not by lenticular movement but by movement of the light source. As described previously, a second light source placed adjacent to the first provided scope for displaying a stereo pair. The operation of such a display is illustrated in Figure 3.

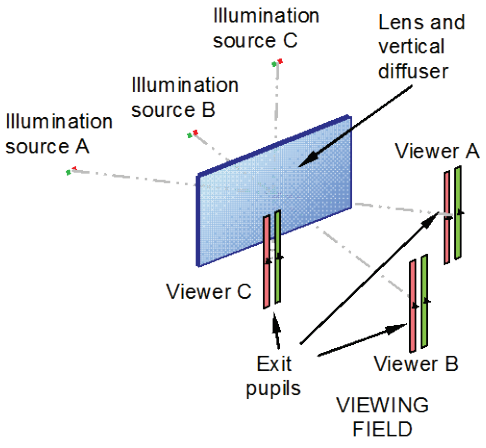

Figure 3 – The operation of an autostereoscopic multi-viewer display using steerable backlight.

The practical realisation of the multi-viewer display was somewhat problematic, however. To counter lens aberrations which would have limited the off axis performance of the system, an array of plate elements was used in conjunction with multiple light sources. One such plate element is shown in Figure 4 below.

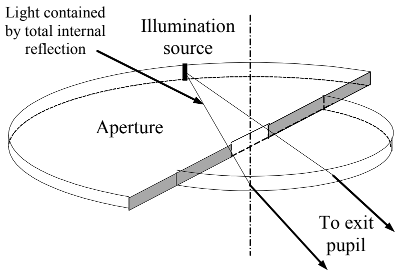

Figure 4 – Plate elements used in the ATTEST project.

The illumination source comprised of 256 white light-emitting diodes (LEDs) located around the perimeter of the rear surface, and ten such identical elements were combined to form the complete array. Furthermore, two arrays were used to form left and right exit pupils. This arrangement had several disadvantages, causing crosstalk between left and right images, high power consumption and lack of brightness.

Although it might have been possible to reduce the crosstalk of the ATTEST display to an acceptable level by judicious selection - and possibly orientation - of the LCD, the lack of brightness was a more fundamental problem. Despite the backlight containing over five thousand LEDs, only a small proportion of these contributed to image brightness. In addition, the physical size and large number of LEDs made the cost of manufacture incompatible with a commercially feasible 3D display.

To solve these problems, an alternative illumination scheme was sought for the MUTED project. By making the rear surface of the plate elements flat, it is possible to couple light into them - allowing a projection technology to be used as a dynamic backlight source.

2.1. Choice of backlight

The LED backlight used for the ATTEST prototype resulted in a dim display, principally due to the spectral characteristics of the white LEDs. It was found that the colour filters present on the LCD panel, used to separate the components of the broadband incident illumination, negated the high electrical-to-optical conversion efficiency advantage gained from using a solid state source. A far better alternative is to use a laser backlight - the red, green and blue components of which each have a narrow spectral bandwidth. If the laser wavelengths are matched to fall within the filter window of the colour filters then all of the energy from the light source passes through the corresponding ‘on’ pixels of the 3D image, leading to a correspondingly brighter display. Careful selection of the wavelengths and powers of the red, green and blue lasers therefore allows for the creation of a bright and efficient white light backlight.

The improvement in efficiency gained by the use of laser light sources makes the architecture correspondingly more dependent upon the choice of projection technology. It is clear from the preceding sections that the rather unusual and exacting requirements placed upon the image source by the optical array - principally, the requirement to display multiple point sources each with well defined spectral characteristics - make the design of the backlight non-trivial.

In this section, the suitability of laser-based imaging, scanning and holographic projection architectures for the projection of high-brightness sparse images is considered. A simple way to measure this is to define a field V_{xy} which is assumed, without loss of generality, to contain $N \times N$ total addressable pixels. Within this field, a proportion of the pixels V_{xy} are illuminated to form an image I_{xy} within some region Ω; the remainder are not illuminated. This arrangement is depicted in Figure 5 below.

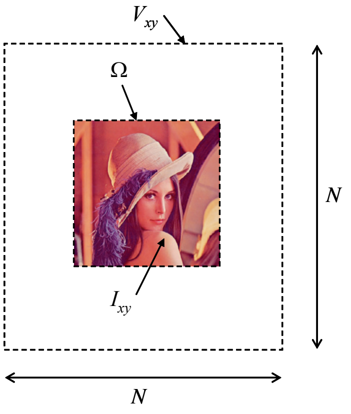

Figure 5 – Projected image geometry for evaluation of sparse image brightness.

The average pixel value η over the entire $N \times N$ field is simply the expected value $E[\cdot]$ of V_{xy} and is given by

$$\eta = E[V_{xy}] = \frac{\sum_{\Omega} I_{xy}}{N^2} \tag{1}$$

where $1/N^2 < \eta \leq 1$. The dimensionless quantity η is therefore effectively a measure of image coverage, in which a smaller η indicates a sparser image.

2.1.1. Imaging

In an imaging projector, laser light of total power P_{las} is expanded onto a $N \times N$ pixel amplitude-modulating display to form the $N \times N$ pixel field V_{xy}. A simple calculation, ignoring the relative effects of the red, green and blue wavelengths and any intermediate optics, shows that the average power P_{av} in each of the illuminated pixels I_{xy} would be

$$P_{av} = \frac{P_{las}}{N^2} \tag{2}$$

For sparse images, where η is low, it is clear that the use of a conventional imaging projector is prohibitively inefficient since the amplitude-modulating characteristic of the display acts to block most of the incident light from the illuminated pixels I_{xy}.

2.1.2. Scanning

Scanning laser systems, which employ one or more micromirrors to raster scan a beam of light, have the potential for increased efficiency compared to imaging systems due to the ability to switch the laser sources off outside the region of interest Ω. Despite this, scanned-beam systems are compromised in terms of brightness by the MEMS action and high laser frequency modulation.

Currently proposed scan architectures are designed to operate in a resonant mode, exhibiting fixed scan angles in the horizontal and vertical directions, so that the mirror visits each of the N^2 pixels exactly once. It is therefore not possible to freely scan the sub-region Ω. Moreover, since the total laser power per video frame cannot exceed P_{las} and because the maximum brightness per pixel is limited by the laser’s modulation bandwidth, it is not possible increase the brightness in Ω – even though pixels outside of Ω are not illuminated.

Therefore, ignoring the electrical drive inefficiencies of driving a green laser at tens of megahertz, the average power in the illuminated pixels formed by a scanning system is simply

$$P_{av} = \frac{P_{las}}{N^2} \tag{3}$$

Comparison of equations (2) and (3) show that current scanned-beam architectures exhibit approximately the same brightness as imaging systems, for a given laser power P_{av} incident on the modulating element.

2.1.3. Holographic

A holographic projector employs a rather different approach to image formation, using a phase-modulating microdisplay on which sets of diffraction patterns are displayed. Upon illumination by laser light of total power P_{las}, the resultant instantaneous projected image appears as a direct consequence of Fourier optics.

In such a system, the phase-modulating microdisplay acts to direct this laser light into all pixels I_{xy} simultaneously, without blocking. The average brightness of the illuminated image is therefore given by

$$P_{av} = \frac{P_{las}}{\sum_{\Omega} I_{xy}} = \frac{P_{las}}{N^2 \eta} \qquad (4)$$

It is clear from equation (4) that the brightness of a holographic projector increases as the image content becomes sparser. This fact is summarised in Table 1 below in which the brightness of scanning and imaging technologies is compared to the holographic projection method, for average coverage values of $\eta = 1\%$, as required for illumination of the MUTED plate arrays.

It is interesting to note that for coverage values of $\eta = 25\%$ and $\eta = 10\%$, which correspond to video and head-up display symbology respectively, holographic projection also exhibits the highest brightness.

	Brightness relative to holographic			
	General case	Video (η~25%)	Symbology (η~10%)	MUTED (η~1%)
Imaging / Scanning	η	1/4	1/10	1/100

Table 1 – Brightness comparison of scanning and imaging technologies, relative to holographic, for varying degrees of image sparseness.

3. The MUTED System

The holographic laser projector used in the MUTED project is an adaptation of a system developed by Light Blue Optics (LBO), designed to precisely match the MUTED optics. The MUTED system comprises a holographic laser projector that is controlled by the output of a multi-target head position tracker, an optical assembly that converts the projector output into steerable exit pupils, and a screen assembly comprising a single LCD panel and image multiplexing screen.

The holographic projector is used to generate carefully tailored spots of light, which are collimated by a field lens so that they enter a horizontal diffuser orthogonally to its surface. The diffuser spreads the light over the complete width of the array elements, a schematic diagram which is shown in Figure 6.

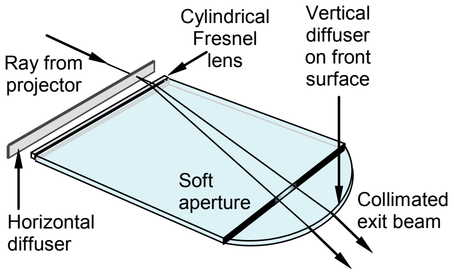

Figure 6 – One MUTED plate element, which takes a diverging ray from the holographic projector and produces a collimated exit beam.

Light emerging from the horizontal diffuser is converged towards an aperture by a cylindrical Fresnel lens whose axis is vertical. This lens is attached to the back edge of a thin rectangular acrylic component where the output from the lens is contained by total internal reflection and channeled towards the aperture. After leaving the aperture, the light is channeled towards the front refracting surface where it exits as a collimated beam formed by the curved front surface. A vertical diffuser attached to the front surface enables the output light to enter the complete height of the LCD; the collimated outputs then overlap at the exit pupil. This system results in the formation of exit pupils in the viewing field, as described by Figure 7.

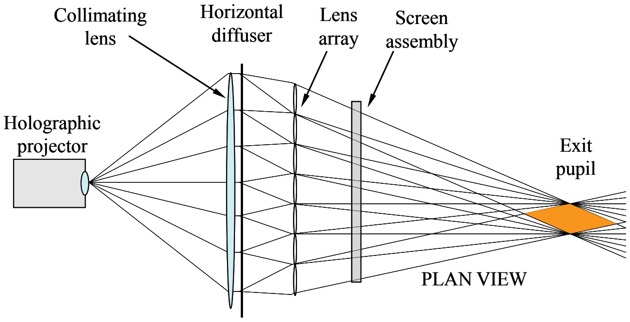

Figure 7 – Optical system diagram, and exit pupil formation, of the MUTED 3D display.

The use of a phase-modulating projection technology is important to this system, since it also allows the optical wavefront at all points in the system to be controlled. This has proven especially important in controlling the uniformity of the MUTED display, where the apparent uniformity of the backlight to the 3D display is determined by the intensity profile of the light output from the optical array.

In the MUTED system, a single element in the optical array produces one strip of illumination for the LCD panel – the spatial intensity profile of which is determined both by the diffusers in the optical array, and the shape of the spots generated by the projector. It was found that to obtain a uniform illumination of the display, the spot shapes should be soft-edged Gaussians. All of the projection technologies discussed thus far are capable of generating such amplitude profiles. However, manufacturing tolerances in the construction of the optical array will inevitably introduce aberrations into the optical path. This can cause the spot shape and size to change, leading to illumination banding and vignetting in the final display. Only LBO's projector, which is capable of controlling the spot phase profile, can be used to correct for field-dependent phase aberrations – thereby recovering the uniformity of the display illumination. A demonstration of this property is provided in Figure 8 below; a significant improvement in the spot shape after projection through the MUTED optics is evident following aberration correction applied at the projector.

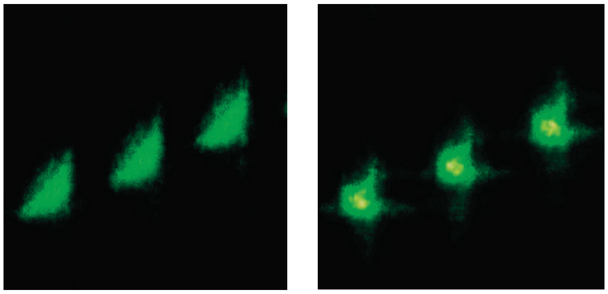
(a) (b)

Figure 8 – Spot shape after projection through the MUTED optics (a) without correction (b) with phase aberration correction applied at the projector

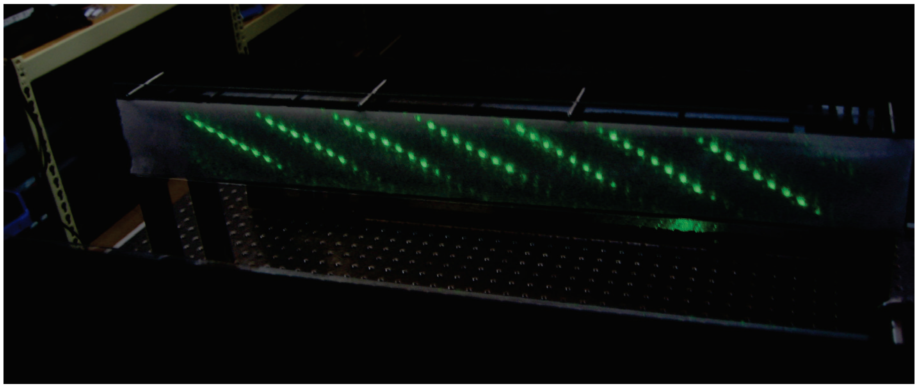

Figure 9 – Spot pattern from the holographic projector, incident upon the MUTED plate elements of Figure 6.

4. Preliminary Results

A monochrome LBO holographic projector was coupled to a plate element to form a movable backlight. As required, the system results in vertical strips of light, which can be dynamically steered across the LCD panel to form the exit pupils in response to appropriate head-tracker coordinates.

The exit pupils were formed by converting a series of spots of light into intersecting collimated beams from two 49-element arrays that are positioned one above the other and situated around 300mm behind the LCD screen assembly. Figure 9 shows a typical spot pattern; the staggered configuration was adopted since the output beam width was considerably narrower than the element width. As the pupil moves laterally the pattern moves laterally in the opposite direction; with increasing pupil distance the horizontal pitch of the pattern decreases. Exit pupils are produced sequentially so that for four viewers, eight pupils are formed; four from the upper array and four from the lower array.

The screen assembly comprises an LCD panel and a multiplexing lenticular screen as per the ATTEST prototype. Temporal multiplexing (where left and right images are presented sequentially) was investigated and the response times of panels from several manufacturers were measured, but unfortunately none of these were sufficiently fast to allow temporal multiplexing.

5. Conclusion

This prototype demonstrates the essential features which the MUTED project set out to prove - namely a multi-user autostereoscopic display which overcomes the size, efficiency and crosstalk limitations evident in the ATTEST prototype. Work continues on the development of the MUTED display, and a full-color system will result in 2008.

6. References

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