A time sequential multi-projector autostereoscopic display[*]

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Abstract

We describe a new 28 view, 25 inch, autostereoscopic display which combines both time sequential and multi-projector technology. It is constructed from four time sequential subsystems, which abut behind a single ferroelectric liquid crystal shutter. The display has a resolution of 512×384 pixels in 24-bit colour. It allows multiple viewers to simultaneously view stereoscopic images without the need for special glasses or headgear.

1. Introduction

Conventional stereoscopic displays use either glasses or a headset to present different images to the user's two eyes. Autostereoscopic displays provide this facility without the need for either glasses or headset. Our group has developed an autostereo display based on the method devised by Travis[1]. By combining Travis' time sequential concept with multi-projector optics we have produced a display which is capable of a larger number of views than the basic time sequential method alone.

In this paper we briefly describe the necessary theoretical background to multi-view autostereo displays and examine the variety of technologies which can be used to implement such a display. We then discuss Travis' concept, the displays which have been built using it, and the advance which has allowed us to overcome its fundamental limitation, increasing the number of views to the point where several individuals can see the stereoscopic image at once, or one can move from side to side to 'look around' foreground objects.

2. Multi-view autostereo displays

Multi-view autostereoscopic displays offer the user three dimensional realism lacking in conventional (2D) displays. In real life we gain three dimensional information from a variety of cues[2]. Two important cues not provided by conventional displays are stereo parallax: seeing a different image with each eye; and movement parallax: seeing different images when we move our heads. Autostereo displays combine the effects of both stereo parallax and movement parallax producing a perceived effect similar to that of a white light hologram.

Multi-view autostereoscopic displays work by displaying multiple different images to multiple zones in space. Figure 1 illustrates the theory behind multi-view displays. Figure 1(a) shows a user looking at a scene in the real world. The user sees a different image of the scene with each eye and different images again whenever he or she moves his or her head. The user is able to view a potentially infinite number of different images of the scene. Figure 1(b) shows a thought experiment in which the same viewing space is divided into a finite number of *windows*. In each window only one image, or *view*, of the scene is visible. However the user still sees a different image with each eye, and the images still change when the user moves his or her head — albeit with jumps as an eye moves from window to window. Thus both stereo and horizontal movement parallax cues can be provided with a small number of views. There is no fundamental restriction to horizontal movement parallax: vertical movement parallax can also be provided, but this squares the required number of views. The finite number of views required in Figure 1(b) allows the replacement of the scene by a display that outputs a different image to each window (Figure 1(c)). This is the principle of multi-view autostereoscopic displays.

Multi-view displays have several advantages over other 3D display technologies:

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- The user is free to place his or her head anywhere within the viewing zone, while still perceiving a stereoscopic image.
- The user can 'look around' objects in the scene simply by moving his or her head (movement parallax).
- Multiple users can be supported, each seeing stereoscopically from his or her own point of view.
- Head tracking, with all its associated complexity, is not required.

The disadvantages of multi-view displays are the difficulty of building a display with many views, and the problem of generating all the views simultaneously[3]. The former problem has been addressed by the system described in this paper. The latter problem is inherent because each view is being displayed all of the time, whether anyone can see that particular view or not.

3. Technologies for multi-view displays

Any one of three broad classes of technology can be used to make multi-view autostereo displays[4]:

- *spatially multiplexed*: the resolution of a display device is split between the multiple views;
- *multi-projector*: each view is generated by its own display;
- *time sequential*: a single very fast display device is used for all views.

The display described in this paper combines features of the latter two.

3.1. Spatially multiplexed

Parallax barriers[5], lenticular sheets[6], and holographic optical elements[7] have all been used to divide the resolution of a display device between multiple views. The display is almost always a liquid crystal device, because this allows relatively simple alignment of the barrier or lenticules with the pixel structure.

The constraints on pixel size and resolution in liquid crystal displays limits traditional horizontal multiplexing to about four views. This is barely sufficient for a multi-view display. However, van Berkel and Clarke have recently demonstrated a seven-view display using a liquid crystal panel and a lenticular sheet[8]. This uses both horizontal and vertical multiplexing to provide several horizontally multiplexed views and gives a 3D display with reasonable resolution in both dimensions

A holographic display[9] uses a very large number of pixels to modulate a light beam. Each pixel is on the order of the wavelength of light in width. This currently requires that the display be mounted on an optical bench to prevent extraneous vibration. A holographic display can be used as a spatially multiplexed autostereoscopic display and, as such, has the potential of delivering hundreds of different views[10].

3.2. Multi-projector

These devices use a single projector for each view[11], projecting their images onto a special transmissive or reflective screen, such as a double lenticular sheet. They suffer from the two problems of expense: one projector per view becomes exorbitant for even a reasonable number of views; and of alignment: the projected images must be aligned precisely with one another.

3.3. Time sequential

Time sequential displays use a single display device running at a high frame rate. A secondary optical component is required to direct the images to the appropriate zones in space. Displays based on Travis' concept[1,12] are of this type.

The advantage of time sequential over the other technologies is that all views are displayed on the same image display, so there can be no mis-alignment between multiple image sources (as in multi-projector devices) nor between pixels and a lenticular array or parallax barrier (as in spatially multiplexed devices). Further, more view directions can be more easily sustained than is currently feasible with a lenticular or parallax barrier display, and a large number of views can be supported less expensively than with multi-projector or holographic devices. The challenges of time sequential autostereoscopic technology lie in producing display devices with sufficiently fast refresh rates, in delivering high enough luminance to be shared amongst the multiple views, and in designing the view direction modulating optics.

3.4. Hybrid systems

Combining two of the above mechanisms can produce a system with a higher number of views, at the expense of more complex technology. Combining spatial multiplexing and multi-projector has led to prototype 40-view[13] and 72-view[14] displays. A simpler 7-, 13-, or 21-view hybrid system has been designed by Hines[15]. The combination of Travis' time sequential concept with multi-projector ideas has led to the display described below.

4. The Cambridge displays

The new display is based around Travis' concept[1], which is a particular way of making a time sequential autostereoscopic display. Displays based on this concept have traditionally been called "Cambridge displays".

We briefly describe the development of these displays, from ideal design through monochromatic implementation to colour implementation, as it is central to an understanding of the new display.

4.1. Ideal design

The design of an ideal Cambridge display as invented by Travis[1] (Figure 2(a)) consists of a high speed liquid crystal display, a Fresnel lens, and a series of abutting bar shaped light sources. The light sources are placed just beyond the focal plane of the Fresnel lens so that an image of the light bars is projected into the user's view space; this image of the light bars is termed the *eye box*. Each light bar is illuminated in turn and, in synchronisation with this, successive laterally adjacent views of an object are displayed on the liquid crystal display. The effect of the lens is that each view is visible in a different window in front of the display. Provided that the views are repeatedly illuminated sufficiently rapidly, the user will perceive a three-dimensional image with both stereo and horizontal movement parallax, so long as both the eyes are within the eye box. While the best position from which to view autostereo images is at the eye box, a good 3D effect is obtained over a large range of distances. For example, the 10 inch Cambridge display[16,17] has a best viewing distance of one metre, but produces a 3D effect from 50 cm to several metres. A full analysis of the viewing zone can be found in Dodgson[18].

Eight views displayed at a 60Hz refresh rate require a liquid crystal display with a field rate of 8×60 Hz = 480 Hz. A more desirable 32 views would require almost 2 kHz. Neither speed is presently feasible with nematic liquid crystals, but may be attainable with ferroelectric (smectic) liquid crystals if the problem of transferring image data sufficiently quickly to the liquid crystal array can be overcome[19].

4.2. Practical design

A practicable monochrome sixteen view version of a Cambridge display was developed by Travis, Moore, Lang, Dodgson and Castle[16,17,20]. It utilises a high speed CRT, an 'image transfer' lens, and a ferroelectric liquid crystal shutter element. These emulate the light sources and transparent display screen of the ideal version (Figure 2(b)). It is capable of 16 views at 320×240 resolution or 8 views at 640×480 (both interlaced) on a 10 inch (254 mm) diagonal screen. This requires horizontal and vertical scan rates of 150 kHz and between 400 and 1000 Hz, to give individual view direction refresh rates of 50–60 Hz, and an eye box of about 250 mm width at a viewing distance of 1 metre.

This CRT-based display can be considered to be two superimposed optical systems: a compound image transfer lens, which transfers an image of the CRT into the plane where the liquid crystal display would be in the ideal version, and a 10 inch diagonal Fresnel lens, which projects an image of the shutter into space. The image transfer lens does not project a real image; rather the user looks through both Fresnel and projection lenses and directly views the CRT faceplate, like looking through a magnifying glass. This means that the optical system is much more tolerant to aberrations than a true projection system would be, and the image luminance does not depend on the magnification of the system.

The device works by displaying each view in turn on the CRT. One of the liquid crystal segments of the shutter is made transparent in synchronisation with the image display. This directs the light from the CRT to a specific window in the eye box. In terms of geometric optics, the image transfer lens transfers the image on the CRT face to a plane in free space. The Fresnel lens is placed at this plane, so that an image of the CRT appears to lie on its surface. The liquid crystal shutter is placed where the array of light sources would be in the ideal version, taking the front elements of the projection lens into account. The CRT based version is thus functionally identical to the simpler ideal version. However the size of the eye box has an absolute limit on it, because the diameter of the transfer lens has to be as big as the width of the shutter. Transfer lenses of aperture *f*1 are readily available (intended for the projection TV market).

The shutter must switch completely in the vertical flyback interval. A nematic shutter is too slow, so a ferroelectric shutter with switching time of less than 100 μs was used. The ferroelectric shutter decreases the luminance of the viewed image by a factor of T_p/N, where T_p is the transmission of the shutter's polarisers in the open condition (approximately 35%), and N is the number of view directions. For 16 views, this gives an optical transmission of about 2%, requiring a bright image source. A standard 9 inch projection CRT with a short-persistence (75 μs) ZnCdS P4 phosphor was used, which had a maximum screen luminance of 27,000 cd/m^2. Overall light loss through the optical system is dominated by the optical transmission of the shutter system, but there are also losses due to the lenses and to unwanted reflection off the rear surfaces of the many optical elements in the system. Peak stereoscopic image luminance was measured and found to be greater than 300 cd/m^2.

4.3. Colour

All Cambridge displays built before 1995 were monochrome[16,17]. Colour was achieved in late 1995 using a colour sequential solution, since shadow-mask based colour CRTs are not capable of the required luminance. A Tektronix nematic liquid crystal colour shutter was used to dynamically filter the light from the P4 monochrome

CRT[12]. This was a multi-segment shutter, and was fitted at the position of the ferroelectric shutter so that the segments of the colour shutter followed the segments of the ferroelectric shutter as they scanned across the lens aperture, in the same way that the colour shutter segments were designed to scan down the CRT face[21]. The red channels of all of the views were displayed first, followed by the green and then the blue. This allowed the slow-switching (2–3 ms) nematic colour filter to be used with vertical scan rates apparently faster than its switching speed because, at any given point in time, the segments of the colour filter which were undergoing transition were hidden by opaque sections of the view direction shutter. The disadvantages of this solution were that the number of views was divided by three (because each view direction had to be displayed three times: once each for red, green, and blue) and the red output of the P4 phosphor was low. This reduced the maximum possible number of views from sixteen to six and decreased the peak white image luminance to 48 cd/m^2 . It also had a non-standard interface: most frame stores are designed to output the three colours in parallel, not in series. However it required no modification of the existing optics, and there could be no misalignment between the three colour channels, because each is displayed on the same device in exactly the same place.

Improvements in turn-off times and circuit design of high voltage deflection semiconductors have allowed the deflection rates of the colour Cambridge display to be increased so that it is now capable of 7 views in a colour sequential system at a resolution of 512×384 pixels[22] , with horizontal deflection frequencies of 285 kHz, flyback of 1.2 μs, vertical deflection of around 1200 Hz, and pixel clocks of around 230 MHz. This improves the stereo resolution but still does not offer a sufficiently large number of views to give a large enough eye box to be commercially attractive. The time sequential autostereo solution is limited by the speeds of the CRT: field rate, line rate, and pixel clock. The various speeds are tabulated in Table 1, with comparisons against other standards. CRT technology is very flexible and, to some extent, these speeds can be traded off against one another: more views at a lower resolution or fewer views at a higher resolution. 7 views offers a good trade-off between views and resolution.

Dropping from 7 views colour sequential to 5 views would allow a resolution of at least 640×480[23,24]. However, the number of views is too few for practical use (our experience leads us to believe that, for comfortable viewing, a multi-view display needs at least 6 views and an eye box at least 200 mm wide). Whilst a doubling of the current deflection speeds for CRTs is conceivable, an order of magnitude change is unlikely. A lesser limitation on this device is its brightness: the more views there are, the dimmer an individual view will be for a given CRT peak luminance. It was thus necessary to investigate alternative methods of increasing the number of views.

5. The new display

It is obvious that multiple CRTs and projection lens systems can be placed behind a single Fresnel lens. Moore and Lang experimented with this idea, using multiple CRTs to produce an autostereo display with multiple eye boxes. Martin (and colleagues) subsequently developed a practical way of abutting the multiple eye boxes. It was shown that the shutter need not be located in the middle of the image transfer lens. An image transfer lens was designed with a planar final face against which the shutter could be placed. The lens is designed such that rays from each pixel will pass through every point on the final face (and hence on the shutter) on their way to forming the image of that pixel (Figure 3). This advance allowed us to overcome the limitations on the basic display, of both transfer lens size and number of views, by using multiple CRTs, abutting multiple projection lenses behind a single large shutter. This combines the multi-projector and time sequential concepts.

The fundamental requirement of an autostereo display is that an eye box is formed in space. The eye box contains many windows, from each of which a different image is visible. These images must all appear to be formed in the same place on the same plane. The display thus has a single large Fresnel lens imaging a single shutter to a single large eye box. Immediately behind the shutter are a multiplicity of image transfer lenses, each casting an image of a CRT onto the large lens (Figures 3 and 4).

Tracing rays from the eye box through the corners of the Fresnel lens to the shutter shows that this system can work, provided that the front lenses of adjacent image transfer lens systems abut. This is only possible because the shutter can be placed at the very front of the lens. The vertical dimension of the shutter is set by the f1 limit on the transfer lens. The horizontal dimension of each individual lens is set by how close the image sources can be packed. A four CRT system has been built. Each lens has the same optical components, but they are aligned slightly differently for the two outer projectors than for the two inner projectors.

The limitations on the number of lenses that can be packed horizontally is set by the distortion in the eye box that can be tolerated as one moves off-axis. The display can be constructed with as many projection subsystems as required (within reason) and these could be positioned both horizontally and vertically to make a much larger eye box than is possible with a single projector. Each subsystem has its own CRT and delivers seven colour views. The display could be made with just a single subsystem, producing seven views, but this is barely reasonable for a single user. Two or three subsystems (14 or 21 views) give an acceptable display designed to be used mainly by one user at a time. Obviously, other users can look over the main user's shoulder and they will also see a 3D image as long as both eyes are in the eye box. This allows some degree of collaborative working. For full, side by side, collaboration four subsystems can be used — giving a total of 28 views. Other users can watch over the two main users' shoulders, providing a truly multi-user 3D display without special glasses.

5.1. Construction

The transfer lenses are rectangular in aperture, 76 mm wide by 112 mm high, and permit the use of smaller CRTs than the original display, since for an *f*1 design lens, the focal length could now be shorter. Special, 6 element lenses were designed, constructed, and set up with the CRT faceplates in a quasi-Scheimpflug configuration so that the transferred images of the 4 CRTs fell on the plane of the 25 inch diagonal (635 mm) Fresnel lens. The design viewing distance of the eye box from the Fresnel lens was 2300 mm. The whole optical path was folded using 2 plane front-surfaced mirrors to save space (Figure 5).

A 4 inch diagonal, 55°, 36 mm neck diameter CRT was chosen, with a red-enhanced phosphor similar to P4 using a mix of ZnCdS red and green phosphors and ZnS blue. Vertical deflection frequency was 1260 Hz with 150 µs flyback. Running at 286 kHz horizontal scan with approximately 1.2 µs flyback and 223 MHz pixel clock allowed 21 monochrome views at 512×384 resolution interlaced, with each individual full colour view refreshed at 30 Hz interlaced. The 21 views are used in the colour sequential system to deliver 7 full colour views from each CRT. A 28 segment ferroelectric shutter was designed with an active area of 125×308 mm, and placed in front of the lens array. It was not practical to have manufactured a special nematic colour shutter to be fitted with the ferroelectric shutter, so individual ferroelectric 80×80 mm active area colour shutters[25] were fitted within the transfer lens, and switched in the vertical flyback time.

Moore designed custom electronics for the CRT deflection, the ferroelectric directional and colour shutters, and the convergence circuitry so that the images from all of the CRTs could be precisely aligned on the Fresnel lens.

5.2. Image Sources

The 28 view display requires a pixel rate of 223 MB/s on each of its 4 subsystems to display full-rate 24 bit video. Each CRT channel was driven by an individual DEC Alpha computers and Datapath Merlin II graphics card, which supplied the necessary 7 view signal. The 4 Alphas were synchronised and controlled by a fifth Alpha, and could provide approximately 30 seconds of continuous full motion animation, using pre-rendered images. Whilst the display is capable of full analogue colour, the storage constraints on the image source required the use of 8 bit colour, with colour palettes on the graphics cards to provide the range of colours required. Each individual image was displayed for 3 successive vertical scan periods, and the RGB outputs multiplexed in the display to give the sequential colour signal required by each CRT.

Live video input requires a mechanism for multiplexing multiple camera inputs into an appropriate video stream. Dodgson and Moore have designed such a camera multiplexing system[26,27]. It can take inputs from up to 16 cameras and multiplex these for display on a time multiplexed autostereo display. They have built a prototype which can handle up to 8 cameras. Four such multiplexers would be required to feed live autostereo video to the four subsystems of the new display, each multiplexer handling 7 cameras.

5.3. Results

The user sees a 25 inch diagonal, full colour, 3D image with a total of 28 views.

5.3.1. Eye box and views

The eye box is positioned 1200 mm from the front lens. A stereoscopic effect can be achieved from 650 mm to 2200 mm. Each view occupies a width of about 21 mm in the eye box. The overall eye box size is 584×178 mm (about 2 feet wide), allowing two people to work side by side. Average human eye separation is 65 mm; the average user therefore sees views three apart, providing a good three-dimensional illusion. In each CRT channel, the images are separated by the gap between the shutter elements (approximately 80 µm) which is unnoticeable to the eye, although images with great depth show the usual discontinuity as the boundary is crossed[18]. The junction between the output lenses of each individual CRT channel is more noticeable, particularly at the sides, where misalignment of the lens is greater (Figure 6). Adding a low power vertical lenticular sheet on the plane of the Fresnel lens diffused the image gap sufficiently to make it unobjectionable without materially affecting the image luminance or sharpness.

5.3.2. Luminance and contrast

Luminance was measured directly from the CRT screen or from the viewed image using a Minolta LS100 luminance meter on a tripod support, viewing a small square lit-up element larger than the sensing area of the meter, but sufficiently small so as not to bring the CRT average beam current above its maximum rating.

Peak white luminance in each individual view channel is 85 cd/m^2 (25 ft/L), at which the CRT spot is starting to defocus. Useable maximum luminance is 68 cd/m^2 (20 ft/L). This can be improved by 50% by using a high-efficiency polariser in the shutter (42% transmission instead of 35%), which was not easily available, in the size required, at the time of construction. Contrast ratio is measured at better than 100:1 — but the user is looking through an optical system with a Fresnel lens as the viewing surface, so this depends greatly on the specular reflection from the Fresnel surface. The viewing area needs to be heavily hooded because of the wide angle over which the Fresnel lens 'sees' light sources.

5.3.3. Phosphor and ghosts

The ZnCdS phosphors used are only just fast enough (approximately 70 μs decay time to 10%) for the system, and also suffer from an extended non-exponential decay 'tail'. The ghost image (the remains of other view images in a single view) which are the bane of stereoscopic systems are caused by the phosphor decay and any lack of switching contrast in the directional shutter. The directional shutter contrast ratio was found to be better than 200:1 by testing with a CRT with a very fast decay (approximately 160 ns decay time to 10%) P43 phosphor, so gives only 0.5% ghosting, which is entirely acceptable. The P43 phosphor, whilst very fast, is a rare earth line emission phosphor with poor efficiency (about 5 lumens/watt, 10% of the ZnCdS green) and only available in green. However its fast decay time makes it the standard on which other phosphors are judged, and enables the performance of the shutter to be tested and the polarisers and switching adjusted unobscured by phosphor decay effects.

The effects of ZnCdS phosphor decay cause a general 2% ghost from all views in a single CRT channel, with approximately 5% ghost on the immediately adjacent view. This interferes with the stereoscopic effect for high-contrast images with great depth (e.g. line drawings on a black background) but is almost imperceptible on normal video images with a high average luminance, although it can detract from the 'crispness' of the image.

ZnCdS phosphors are not usually fitted to projection CRTs because they saturate easily and have a relatively broad-band emission. In this case the high refresh rate reduces the effect of phosphor saturation, which is only just becoming apparent at a screen luminance of 34,000 cd/m^2 (10,000 ft/L) and, even then, only because a finer spot electron gun was used in the CRT than was actually required for the image resolution.

5.3.4. Convergence and Optics

Each individual CRT's 7 views inherently overlay each other on the Fresnel lens, but the separate CRT channels must be mechanically and electronically aligned. To avoid eyestrain the images should ideally be on the same surfaces, with no more than 5 minutes of arc vertical misalignment from the viewing position in prolonged separately viewed images[28]. This is equivalent to a 3 pixel offset when viewed from the ideal viewing position. Spherical aberration in each optical channel means that as the viewing point is shifted sideways, the image surface changes shape (bows away from or protrudes towards the observer), with changes in the absolute depth. This is hidden in a single channel by the stereoscopic effect, but if the user's eyes are in two separate channels it is more noticeable. No relative measurements were made between separate channels. There was some movement due to the spherical aberration of the lenses, but there have been no reported problems from users unable to acquire the stereoscopic image.

The electronic convergence was set for best image overlay for the images cast onto a translucent screen at the position of the Fresnel lens, with the shutters disabled. Analogue circuitry similar to that used in delta-gun TVs was used for simplicity, which gave the usual 2–3 line width mis-convergence at image extremes, but was found in practice to be unnoticeable on moving images, even when the user was moving his or her head.

5.3.5. Conclusions

The display, as presently constructed, is useable for a range of applications not requiring high luminance. Improvements in the lens design (e.g. a single piece front element across the entire shutter, and aspheric design to improve aberrations) will give improved viewability, and phosphors with less of a tail would improve the stereoscopic usefulness.

6. Summary

We have developed an autostereoscopic display by combining Travis' time sequential concept with multi-projector optics. This development has allowed us to produce a display with a large screen (25 inch diagonal), an eye box sufficient for several simultaneous viewers, and a reasonable number of views. Ongoing research will consider how to combine multi-projector and parallel-colour ideas to produce larger, higher resolution and brighter images[23,24].

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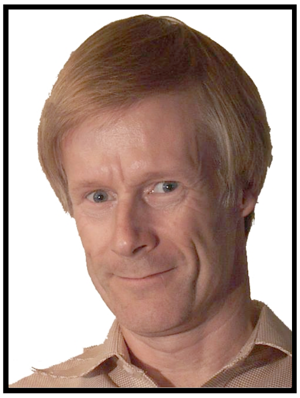
Neil Dodgson received his BSc degree in Physics and Computer Science from Massey University, New Zealand in 1988 and his PhD from the University of Cambridge in 1992. He has worked on the autostereo display project since 1990, investigating both hardware and software issues. He is currently a University Lecturer in the Computer Laboratory at Cambridge where he co-leads a research group in computer graphics and image processing. Dr Dodgson is a Fellow of Emmanuel College, Cambridge, a Member of the IEE, and a Chartered Engineer.

John Moore received his BSc degree in Physics and Electronics from Manchester University, UK in 1965. He worked in industry with ICL and EMI on data transmission and visual displays. He jointly set up Manitron Displays in 1979, designing and manufacturing top end graphics and raster radar displays, and left to form the consultancy JMEC in 1989. He received his PhD on the autostereo display from the University of Cambridge in 1997. He is presently working as a consultant on the 3D display with ASD Systems. Dr Moore is a Member of the SID, the IEE and a Chartered Engineer.

Stewart Lang received his BSc in Electronics & Electrical Engineering from the University of Manchester in 1970, and his PhD from the University of Cambridge in 1976 for his research on interactive graphics at the Computer Laboratory. From 1975 he worked on compiler and operating system development in the UK and USA, and returned to Cambridge in 1991 to work on autostereo displays. Since 1994, he has been CEO of ASD Systems, a company set up to exploit the autostereo display technology developed in Cambridge. Dr Lang is also a Research Visitor in the Computer Laboratory at Cambridge, a Fellow Commoner of Sidney Sussex College, Cambridge and a Visiting Professor of Computer Science at the University of Glasgow.



Graham Martin obtained a B.A. in Physics at Oxford University, England in 1972 and a Ph.D in Physics from the University of Southern California, Los Angeles, in 1978, working mainly in the area of non-linear optics. He has spent most of his time since at Litton Guidance and Control Systems in Woodland Hills, CA, studying concepts for optical guidance systems. Since 1996 he has been the technical lead for Litton's effort in developing the time-multiplexed 3D-display technology. He holds more than a dozen patents in these fields.

Peter Canepa received his BS in Physics from the Massachusetts Institute of Technology in 1962. He was on the staff of the MIT Draper Laboratory working on the Apollo moon landing program through Apollo 15. After receiving his MBA from Boston University in 1972, he has held executive R & D and business management positions at ITT, Litton and Interstate Electronics. Since 1995 he has been chief technology officer of Infinity Multimedia International in Sherman Oaks, California. Mr Canepa is a Member of the SID, the IEEE and the ACM.

Figures and tables

	NTSC (ITU-R BT.601)	HDTV (SMPTE 240M)	1995 Cambridge display[12]	New display
Pixel clock	13.5 MHz	74.25MHz	75MHz	223MHz
Line rate	15.7kHz	33.8kHz	150kHz	286kHz
Field rate	60 Hz	60 Hz	1020Hz	1260Hz
Cycle rate	30 Hz	30 Hz	30 Hz	30 Hz
Resolution	720×480	1920×1035	320×240	512×384
No. views	1	1	16(17)	7

Table 1: A comparison of various CRTs' parameters. The 1995 Cambridge display had 17 views in its cycle but only 16 of these were used to display images to the viewer. All displays are interlaced, with two fields per view.

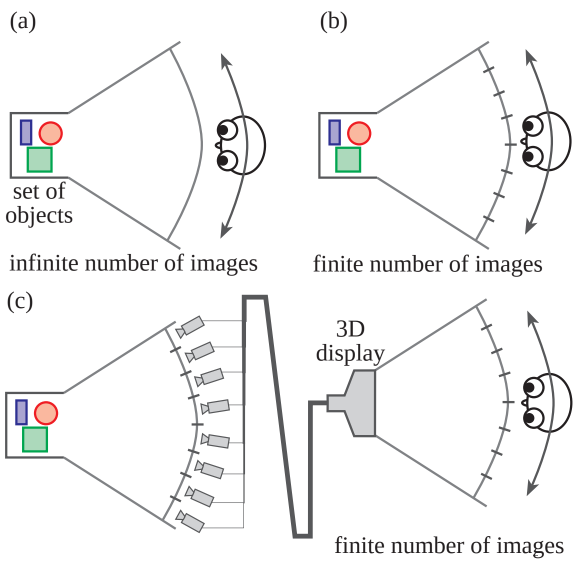


Figure 1: (a) When viewing a scene in real life, a user sees a different image with each eye: stereo parallax. When he moves his head he sees different images: movement parallax. There are an infinite number of different images of the scene that he could see. (b) The number of different images is made finite, each visible in its own window. Each eye still sees a different image: stereo parallax, and different images are seen when the head is moved: movement parallax. (c) An autostereoscopic 3D display provides a different image to each window, producing both stereo and movement parallax with a small number of views.

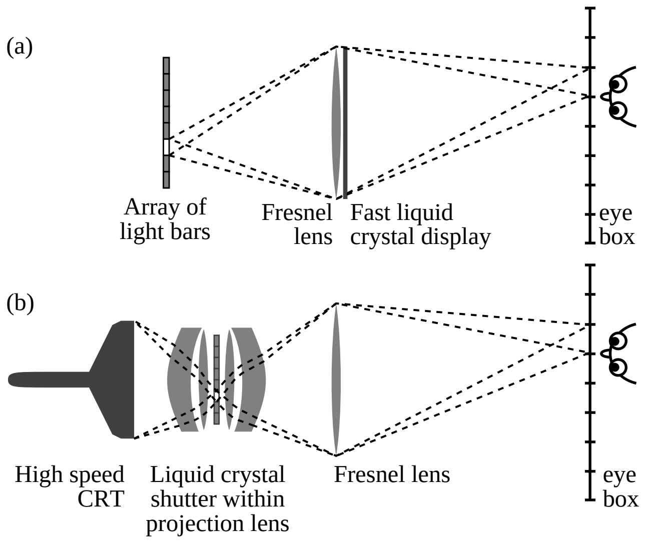


Figure 2: (a) An ideal Cambridge display.
(b) A practicable Cambridge display.

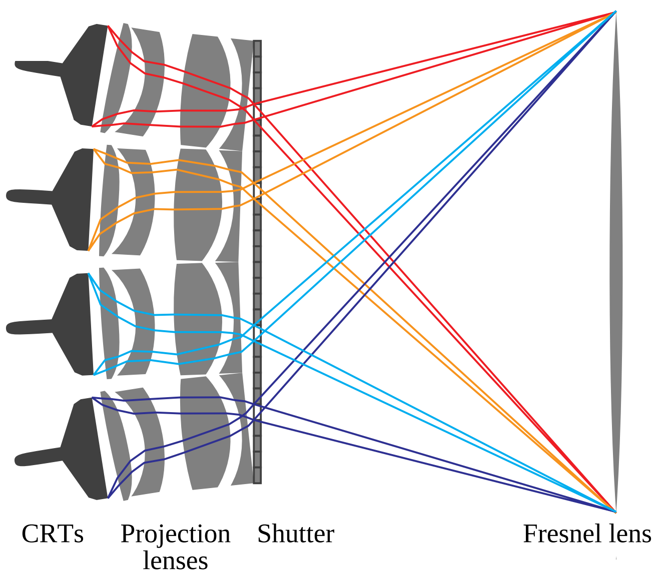


Figure 3: The new 28 view, multi-projector, time sequential display. Multiple CRTs and their associated projection lenses are placed behind a single shutter. The front elements of the lenses abut. Note that the compound lenses in this figure are indicative only; they are not exact representations.

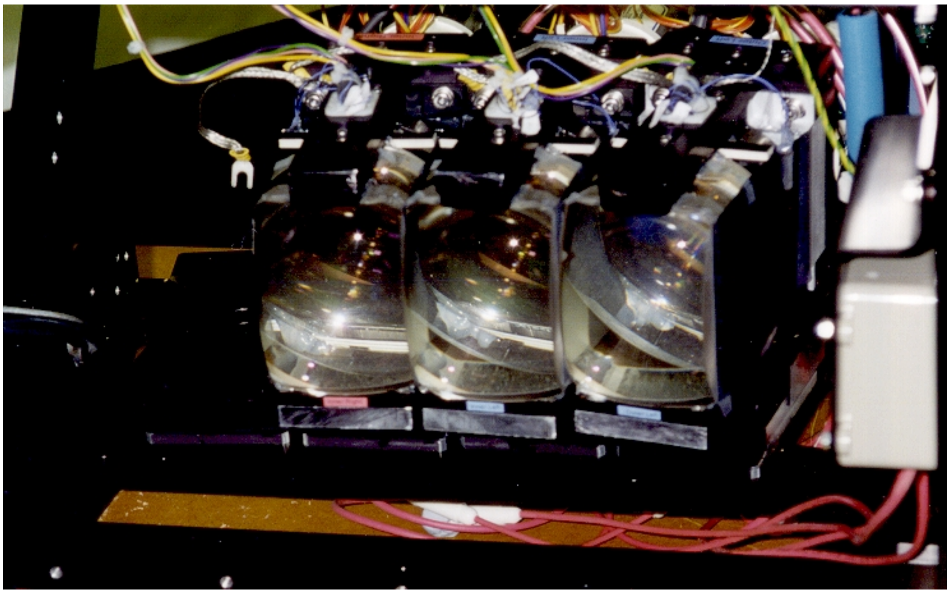


Figure 4: The display under construction. This picture shows the front elements of three of the four projection lenses. The fourth will be placed in the space at left and the shutter then placed in front of all four.

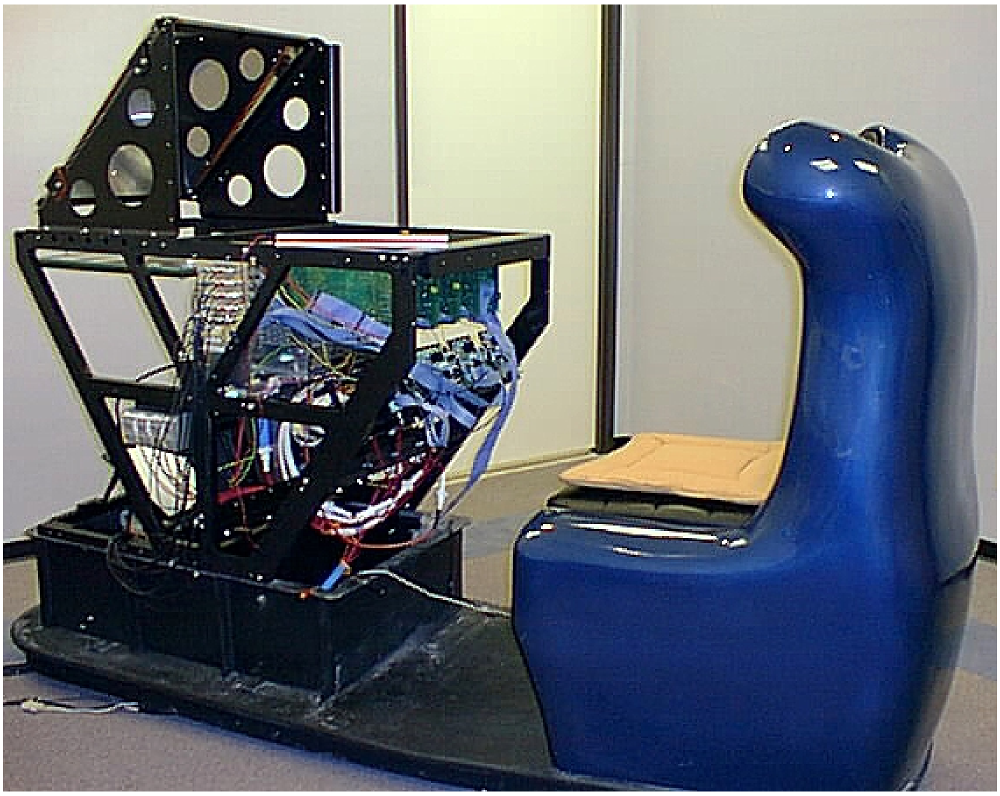


Figure 5: The completed display. The viewer sits in the large chair and views the horizontally mounted Fresnel lens via the diagonally mounted plane mirror. Beneath the Fresnel lens is a second plane mirror. The CRTs and projection lenses are mounted in the right hand half of the housing.

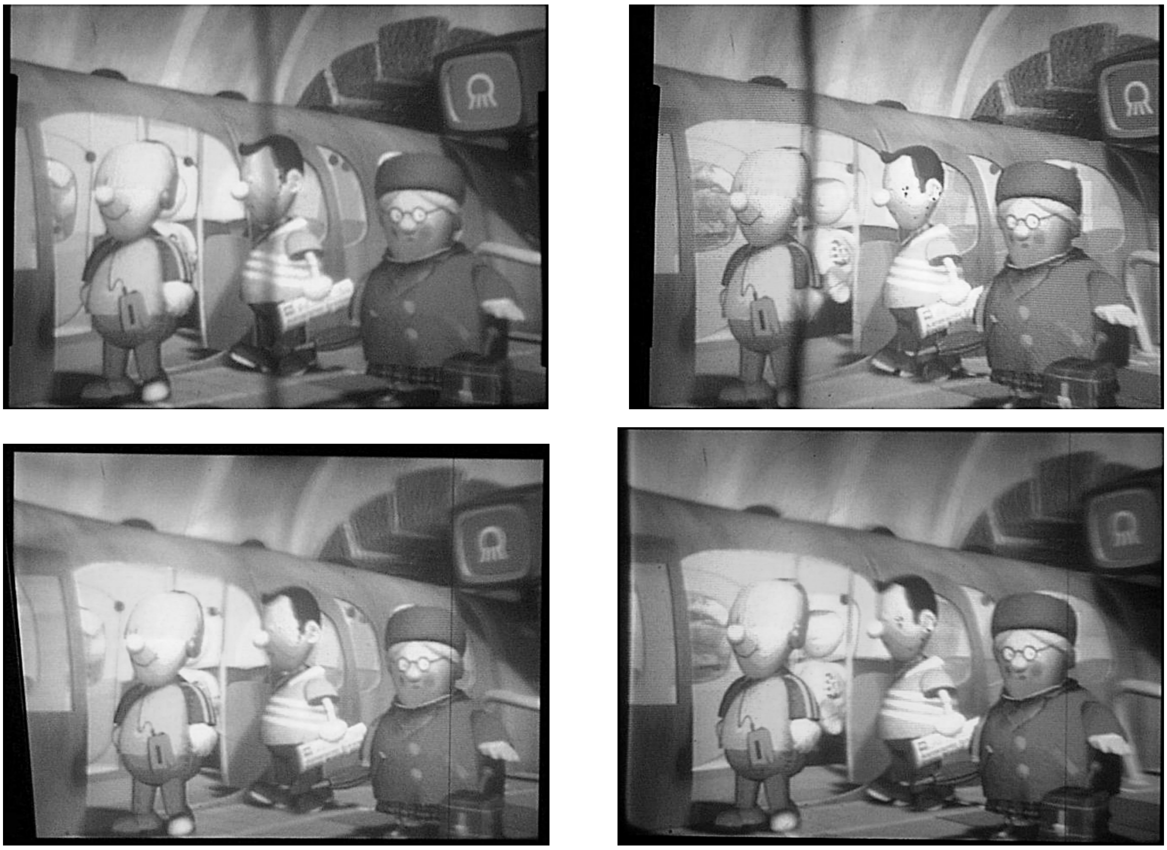


Figure 6: Photographs of the display with and without the lenticular diffuser. The dark line in each of the upper images (no lenticular diffuser) is caused by the join between two optical systems. The lenticular diffuser removes this effect without detriment to image quality.

Upper Left	Centre seam between adjacent CRT Channels without lenticular diffuser
Upper Right	Right seam between adjacent CRT Channels without lenticular diffuser
Lower Left	Centre seam between adjacent CRT Channels with lenticular diffuser
Lower Right	Right seam between adjacent CRT Channels with lenticular diffuser