

A 50" time-multiplexed autostereoscopic display

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ABSTRACT

We describe the development and construction of a large screen version of the Cambridge time-multiplexed autostereo display. The new device uses a 50 inch diagonal spherical mirror in place of the 10 inch Fresnel lens of the original Cambridge colour display. A fivefold increase in image luminance has been achieved by the replacement of sequential colour on a single CRT with separate red, green, and blue CRTs. Fifteen views are displayed at 640×480 (VGA) resolution with about 250 cd/m² luminance and 30 Hz (TV) interlaced refresh rate. A 22 mm inter-view separation provides three views between a typical viewer's eyes, giving a smooth stereoscopic effect over a 330 mm wide eye box.

Two identical optical systems have been built, sharing the single large spherical mirror, allowing simultaneous use of the device by two viewers. The two systems are off-axis with respect to the main mirror, requiring geometric compensation on the CRTs in addition to the normal colour convergence.

The prototype produces two independent full colour, large, 3D images which can be viewed under normal lighting conditions.

Keywords: autostereoscopic, stereoscopic, time-multiplexed, 3D, display, Cambridge autostereo display

1. INTRODUCTION

We describe the development and construction of a large screen version of the Cambridge time-multiplexed autostereo display. The new device uses a 50 inch diagonal spherical mirror in place of the 10 inch Fresnel lens of the original Cambridge colour display [MDTL96]. This fivefold increase in linear measure (25 times the screen area) has been accompanied by several other modifications to the display's design.

A fivefold increase in image luminance has been achieved by the replacement of sequential colour on a single CRT with separate red, green and blue CRTs. The three colour channels are combined by dichroic mirrors and beam splitters. This, in conjunction with the longer optical path of the new device, required the design of a new optical train.

Running three CRTs at 285 kHz line rate allows us to provide 15 views at 640×480 (VGA) resolution with approximately 250 cd/m² luminance and 30 Hz (TV) interlaced refresh rate. We use a 22 mm inter-view separation to provide three views between a typical viewer's eyes, which gives a reasonably smooth stereoscopic effect over a 330 mm wide eye box.

Two identical optical systems were built, sharing the single large spherical mirror, to provide simultaneous use of the device by two viewers, each of whom may see completely different images with no interaction. The two systems are off-axis with respect to the main mirror, which requires geometric compensation on the CRTs as well as the normal colour convergence.

The performance specification for this 50 inch prototype was based on marketing research targeted at aerospace and entertainment applications. The objective of the prototype is to demonstrate a large screen autostereo display capable of real time interactivity with two viewers interacting with both the display and each other. Many of the potential users of the device said that they were looking for a technology which would allow two viewers to see different 3D views at the same time while maintaining close proximity of the viewers to one another in order to provide maximum interaction.

The new display produces two independent full colour, large, 3D images which can be viewed under normal lighting conditions.

2. THE CAMBRIDGE DISPLAY

The new display is based around the so-called Cambridge display, a time sequential device [MDTL96]. We briefly describe this device here, as it is central to an understanding of the new display.

2.1. Ideal design

The design of an ideal Cambridge display (Figure 1(a)) consists of a high speed liquid crystal display, a Fresnel lens, and a series of abutting bar shaped light sources [Trav90]. 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, as 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 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 [Dodg96].

Eight views displayed at a 60Hz refresh rate require a liquid crystal display with a field rate of $8 \times 60 \text{ Hz} = 480 \text{ Hz}$. 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 [TL91].

2.2. Practical design

A practicable monochrome sixteen view version of a Cambridge display, developed by ASD Systems [LTCM92, MTLC92, TLMD95], 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 1(b)). It is capable of 16 views at 320×240 resolution or 8 views at 640×480 (both interlaced) on a 10 inch 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/l 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 uncrossed transmission of the polarisers used by the ferroelectric shutter (approximately 0.35), 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 , and a peak stereoscopic image luminance of greater than 300 cd/m^2 .

2.3. Colour

The original Cambridge display was monochrome [LTCM92, MTLC92]. 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 [MDLT96]. This was a

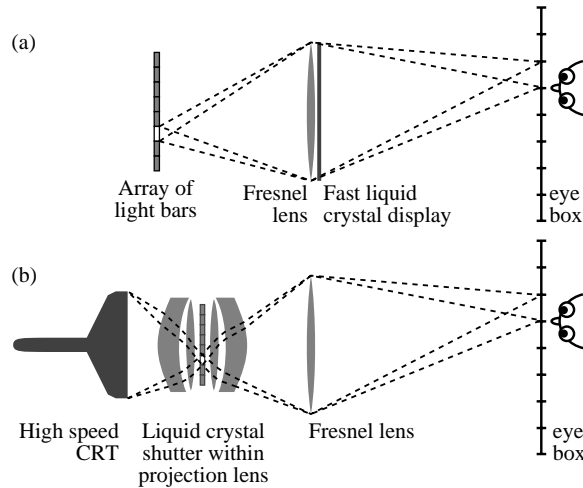


Figure 1: (a) An ideal Cambridge display. (b) A practicable version of the Cambridge display.

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 [BBV85]. This allowed the slow-switching (2–3 ms) nematic colour filter to be used with vertical scan rates apparently faster than its switching speed. 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 Cambridge display to be increased so that it is now capable of seven views in a colour sequential system at a resolution of 512×384 pixels [Cane98], with horizontal deflection frequencies of 285 kHz, flyback of $1.3 \mu\text{s}$, vertical deflection of 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: frame rate, line rate, and pixel clock. 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.

3. THE NEW DISPLAY

The specification that was drawn up for the new display called for two viewing lobes, full colour, a 50 inch screen, and a good resolution in terms of both pixel count and number of views. Each of these requirements was an interesting technical challenge. We discuss, in turn, each challenge and how it was met.

3.1. Resolution

There have now been three distinct versions of the CRT drive electronics. The earliest systems used off the shelf circuitry from a projection TV. The second generation displays [LTCM92, MTL92, MDTL96] used 150 kHz line rate to provide 16 monochrome views at 320×240 pixels (75 MHz pixel clock) or eight monochrome views at 640×480 pixels (150 MHz pixel clock). The third generation displays use 285 kHz line rate. This has been built into the 25 inch display [DMLMC00], providing 21 monochrome views at 512×384 pixels (223 MHz pixel clock). The new 50 inch display required a resolution at least that of VGA (640×480 pixels). By dropping the number of views to 15, the same scan rate (285 kHz) could be used, reducing the flyback time to squeeze in the extra pixels without significantly increasing the pixel clock. This gives a display capable of 15, monochrome, VGA resolution views.

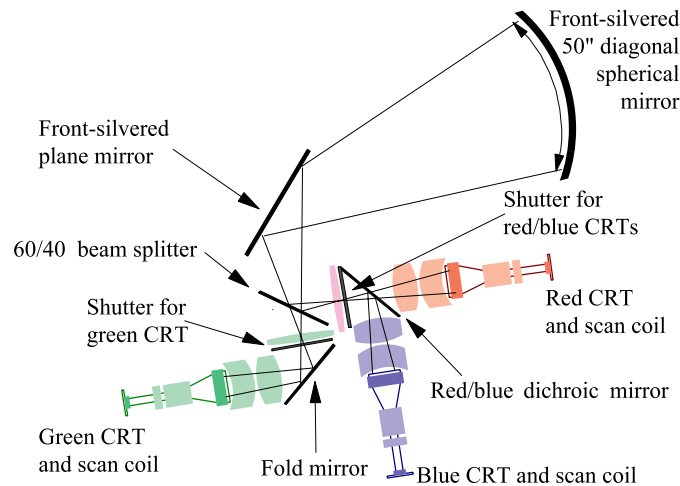


Figure 2: optical design of the new display.

3.2. Full colour

Previous versions of the Cambridge display [MDTL96, DMLMC00] have used a sequential method of producing colour. This involves placing a dynamic colour filter in the optical path, and cycling it through red, green, and blue in synchronisation with display of each colour channel on the monochrome CRT, as described above. This has the advantage of preventing any misalignment of the three colour channels but the disadvantage that it divides by three the number of displayable views. In the second generation display, it reduced 16 views to just six; in the third generation 25 inch display it reduces 21 views to seven.

We eschew the use of head tracking and so must provide a reasonable number of views in order to allow an acceptable amount of head movement. We believe that, for comfortable viewing, a multi-view display needs at least six views and an eye box at least 200 mm wide. A commercially viable device is likely to require at least twice this number of views. The 25 inch display solved this problem by using four seven-view sequential colour systems in a multi-projector configuration, providing a total of 28 views over a 600 mm wide eye box [DMLMC00].

Our experience with the 25 inch display led us to revisit the question of whether we could use parallel colour for the 50 inch display. It had always been our intention [MDTL96] to investigate the use of parallel colour. As the 50 inch display required a complete redesign of the optical train, it seemed reasonable to attempt to investigate parallel colour solutions as part of the design process.

In order to combine three CRTs, it is necessary for there to be sufficient space within that the optical design to allow for the combining elements. The solution that we implemented uses a dichroic mirror to combine the images from the red and blue CRTs. This is then passed through a 60/40 beam splitter to combine it with the image from the green CRT. This solution allows us to use a dichroic mirror with transition band in the green part of the spectrum, so very little light is lost from the red and blue CRTs at this stage in the combining, and there is no variation in transmitted light with variation of incident angle near the cut-off wavelength. The green CRT has a considerably brighter phosphor than either red or blue CRT and so a 60/40 splitter allowed us to pass a greater proportion of red and blue light through than would otherwise have been possible. This provided a high brightness colour image which can be viewed under normal lighting conditions. Figure 2 shows the overall design of the optical system Figure 3 shows a photograph of the heart of the optical sub-system.

3.3. Large screen

Producing a 50 inch diagonal autostereoscopic display necessitated careful design. All other versions of the Cambridge display use Fresnel lenses at the front of the device. A naive user would call this lens the “screen” of the device, for it is in the plane of this lens that a conventional (2D) image would appear to be displayed.

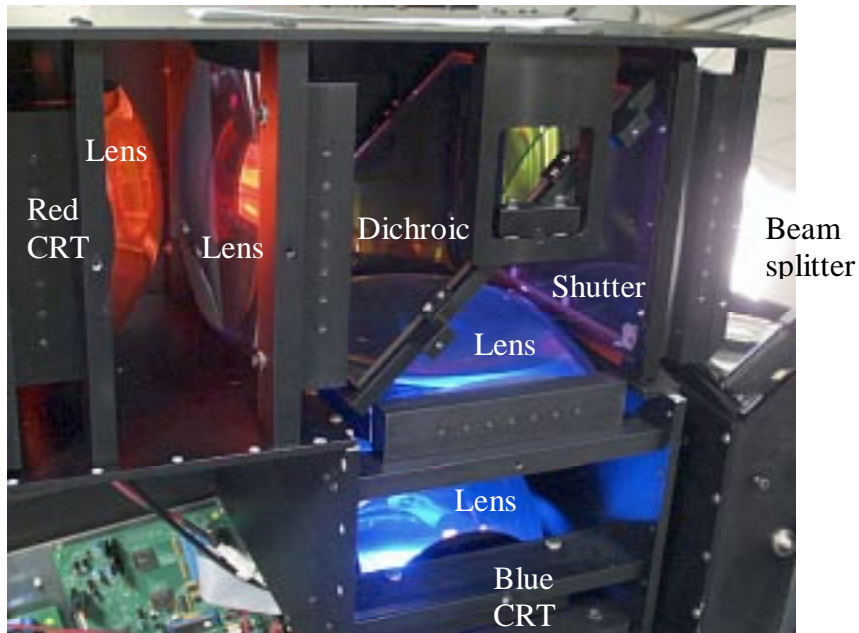


Figure 3: the internal workings of the optical system. The images from the red and blue CRTs are combined by the dichroic. The resulting combination is passed out to the right where it is combined by the beam splitter with the image from the green CRT.



Figure 4: the 50 inch “screen” of the new display, showing a frame from the *Granny* animation.

Fresnel lenses, while useful, have the drawback that they scatter any ambient light, causing unwanted specular reflections. We therefore experimented with both spherical and ellipsoidal concave mirrors in place of the Fresnel lens [DM00]. A prototype 25 inch, seven view display was constructed, using a 25 inch diagonal spherical mirror. Experience with this allowed us to proceed to a design for the 50 inch display which incorporates a 50 inch diagonal concave spherical section as the final optical element.

The image of the CRTs is distorted by the mirror. This is counteracted by sophisticated picture shape correction in the scan circuitry of the three CRTs. Independent control of each CRT’s correction also allows precise alignment of the three colour channels. Figure 4 shows a photograph of the 50” screen.

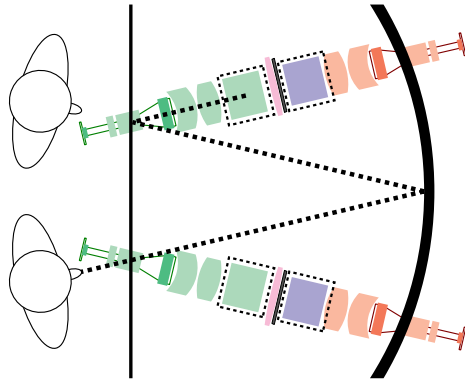


Figure 5: A top down view of the new display. The two viewing positions are shown on left, the 50 inch mirror on right. The two CRT subsystems image are mounted below the curved mirror and image onto it via a plane mirror. The dotted line shows the central optical path from the upper CRT subsystem to the lower viewer via the plane and curved mirrors.



Figure 6: the new display. Left, without casing. Right: with casing. In the right hand photograph we see two viewers standing in the two viewing locations.

3.4. Two viewing lobes

The specification calls for two viewing positions. This was achieved by building two independent CRT subsystems, imaging onto the same spherical mirror. This means that each subsystem is offset both vertically and horizontally from the centre line of the spherical mirror (a single lobe system would have the CRT subsystem aligned horizontally with the spherical mirror). This offset was counteracted, again, by the picture shape correction mechanism. The end result is two 330 mm wide viewing zones, separated by about 1 m. The two zones can show either the same set of 15 views or two different sets of 15 views. Figure 5 shows the positions of the two zones, and the positions of the CRT subsystems relative to the curved mirror.

3.5. Assembly

Each CRT subsystem consists of three CRTs, each with an appropriate short-persistence phosphor, a dichroic mirror, a beam splitter, two identical shutters (one for the red and blue CRTs and one for the green CRT), and various lens elements. These image, via a pair of flat mirrors, onto the large spherical mirror. The entire construction is supported by an aluminium framework. Electronic components are mounted in the space beneath the mirror. Figure 6 shows the completed display, both with and without its casing.

3.6. Image source

The display requires a data rate of about 230 Mpixels/s to display full-rate video. The images are provided by a DEC Alpha and Datapath Merlin II graphics card supplying a 24-bit full colour video signal. It can provide approximately thirty seconds of continuous full motion animation, using pre-rendered images. A variety of pre-rendered sequences are used to illustrate the functionality of the device.

4. DEMONSTRATION

This 50 inch display was first demonstrated in February 1999, in Cambridge, UK. It has since been shown in both Japan and the USA. As we go to press, we expect the next public demonstration, by Litton, of this 15-view 50 inch display to be at Aerosense in Orlando, Florida [MSMLD00]. Aerosense runs from 24–28 April 2000.

5. SUMMARY

The Cambridge autostereoscopic display concept has been successfully re-engineered to produce a large screen, full colour, fifteen view display on which two independent autostereoscopic images which can be viewed by two separate viewers under normal lighting conditions.

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