Time-multiplexed color autostereoscopic display

John R. Moore, Neil A. Dodgson, Adrian R. L. Travis[†], Stewart R. Lang

Computer Laboratory, University of Cambridge, Pembroke Street,
Cambridge, UK, CB2 3QG
[†]Department of Engineering, University of Cambridge, Trumpington Street,
Cambridge, UK, CB2 1PZ

Presented to "SPIE Symposium on Stereoscopic Displays and Applications VII", San Jose, California, Jan 28–Feb 2, 1996. Published in Proc. SPIE vol 2653.

ABSTRACT

A practical color autostereoscopic display has been developed at Cambridge, and has been in operation since 1994. It provides six view directions at half VGA resolution (640 × 240 pixels) of 24-bit color at a luminance of 100 cd/m^2. Each individual view direction is refreshed at standard television rates, so the display is capable of full motion animation or live 3D video. Versions with both 10 and 25 inch screen diagonal have been built. This paper describes the principles of the display, its development from an earlier monochrome version, the results of this development work, and ideas for future research.

The original monochrome display, developed at Cambridge, has been in use since late 1991. It provides eight views at full VGA resolution or sixteen views at half VGA resolution. A series of views of a scene are displayed sequentially and an optical directional modulator, constructed from a liquid crystal shuttering element, is synchronised with the image repetition rate to direct each image to a different zone in front of the display. The viewer's eyes thus see two different images and the head can be moved from side to side to look around objects, giving an autostereoscopic display with correct movement parallax. The use of a CRT makes for a flexible system where resolution and number of views can be easily varied.

Development of the color display from the monochrome version was achieved by a color sequential system using a liquid crystal color shutter. As each view direction had to be displayed three times for the three primary colors, the maximum number of view directions was decreased to six. Full color (24-bit) images have been displayed on these six view autostereoscopic displays from a number of sources: computer generated images, digitised photographs, and live color video from a multiplexed camera also designed at Cambridge.

Keywords: autostereoscopic, stereoscopic, colour, color, 3D display, time-multiplexed

1. INTRODUCTION

Autostereoscopic displays offer the viewer three dimensional realism lacking in conventional two-dimensional or stereoscopic displays. They combine the effects of both stereo parallax and movement parallax producing a perceived effect similar to that of a white light hologram.

In real life we gain three dimensional information from a variety of cues. Two important cues are stereo parallax: seeing a different image with each eye, and movement parallax: seeing different images when we move our heads. Figure 1(a) shows an observer looking at a scene. He sees a different image of the scene with each eye and different images again whenever he moves his head. He is able to view a potentially infinite number of different images of the scene.

Figure 1(b) shows the same viewing space divided into a finite number of horizontal *windows*. In each window only one image, or *view*, of the scene is visible. However the viewer's two eyes each see a different image, and the images change when the viewer moves his head — albeit with jumps as the viewer moves from window to window. Thus both stereo and horizontal movement parallax cues can be provided with a small number of views. There

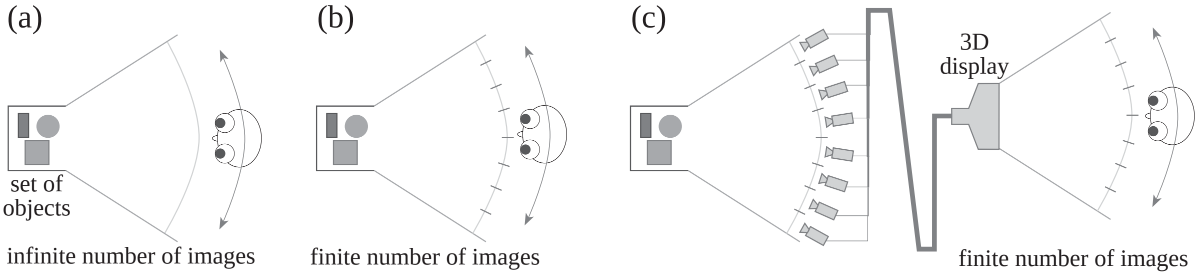

Figure 1: (a) When viewing a scene in real life, an observer sees a different image with each eye: stereo parallax. When he moves his head he sees different images: movement parallax. There are an infinite number of different images of the scene that he could see. (b) The number of different images is 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.

is no fundamental restriction to horizontal movement parallax, vertical movement parallax can also be provided, but this squares the number of views.

The finite number of views required in Figure 1(b) allows the replacement of the scene by a three-dimensional display that outputs a different image to each window (Figure 1(c)). This is the principle of multi-view autostereoscopic displays.

The Cambridge autostereo display (hereafter referred to as the Cambridge display) uses a time-multiplexed system to produce a multi-view autostereoscopic image. Each view is displayed on a CRT, and a dynamic optical system ensures that each view is only visible in a single window in front of the display. The monochrome version is capable of up to sixteen views, the colour version of up to six.

This paper discusses the advantages of time multiplexing over space multiplexing before describing the design of the monochrome Cambridge display. It then describes the development of the colour display from the monochrome version, methods of generating images for the display and directions for the future.

2. TEMPORAL & SPATIAL MULTIPLEXING

Most practical autostereoscopic technologies use spatial multiplexing, limited to horizontal parallax. That is, they use extra horizontal image resolution to produce the multiple views. The challenge of spatial multiplexing is obtaining the necessary horizontal resolution. Thus, a four view lenticular[1] or parallax barrier[2] display requires four times the horizontal resolution of a normal display. For example a four view 640×480 display would require a 2440×480 pixel matrix.

Multi-projector systems[3] can have many more views than lenticular systems. They use one projector for each view, with each projector using a standard sized pixel matrix. Such a system can, however, become prohibitively expensive, because multiple devices must be used and they must be precisely aligned with one another.

A holographic display[4] 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. Holographic displays have the potential of delivering hundreds of different views[5].

Instead of these spatial multiplexing techniques, time-multiplexing can be used to produce an autostereoscopic display. A time-multiplexed *stereoscopic* display can be easily produced by running a conventional display at twice normal speed and alternating two views on subsequent fields[6]. Shuttered glasses are synchronised with the field switching to produce a two view stereoscopic system using a single pixel matrix.

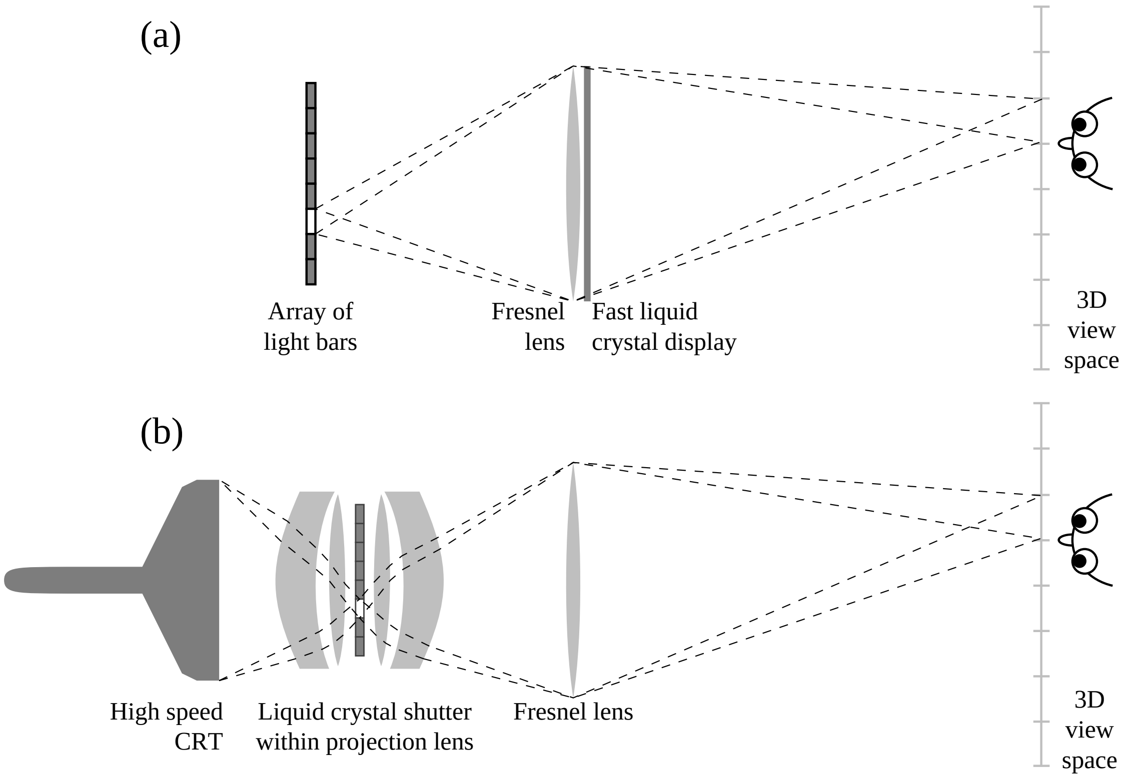

Figure 2: (a) An ideal Cambridge display. Each light bar is illuminated in turn, and the corresponding image shown on the liquid crystal display. The effect of the fresnel lens is that each image is only visible in a specific window in the observer's view space. (b) A practicable version of the Cambridge display. The projection lens casts an image of the CRT onto the fresnel lens. The shutter determines the window in which each image is visible.

A time-multiplexed *autostereoscopic* system requires some way of directing the light from a single pixel matrix, without using any special glasses, so that each view is only visible in a single window. This ensures that each eye sees a different view, and that the viewer can move his head to look around objects in the scene. The Cambridge display provides a way of doing this.

The advantage of time-multiplexed over spatially multiplexed technology is that all views are displayed on the same device, 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. 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 multiplexed autostereoscopic technology lie in producing display devices with sufficiently fast refresh rates and in designing the view direction modulating optics.

3. THE CAMBRIDGE AUTOSTEREO DISPLAY

The basic design of an ideal Cambridge display[7] (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 observer's view space. 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, as shown in Figure 2(a). Provided that the views are repeatedly illuminated sufficiently rapidly, an observer will perceive a three-dimensional image with

Resolution	Num. views	Refresh rate	Field rate	Colour	Interlace	Note
640 × 240	**16**	60 Hz	1020 Hz	monochrome	interlaced	
640 × 240	8	60 Hz	480 Hz	monochrome	**non-interlaced**	
640 × 480	8	60 Hz	540 Hz	monochrome	interlaced	
640 × 240	6	50 Hz	950 Hz	**colour**	interlaced	
640 × 576	8	50 Hz	450 Hz	monochrome	interlaced	live video
384 × 288	6	50 Hz	950 Hz	**colour**	interlaced	live video

Table 1: Various configurations of the Cambridge Autostereo Display. Bold type indicates the primary feature of each configuration. In all cases the aspect ratio of the image is 4:3. In the 640 × 240 configurations each *pixel's* aspect ratio is 1:2. These configurations will also support 320 × 240 pixels.

both stereo and horizontal movement parallax. While the best position from which to view autostereo images is at the image of the light bars, 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 1 metre, but produces a 3D effect from 50 cm to several metres. A full analysis of the viewing zone can be found in [8].

Eight views displayed at a 60 Hz refresh rate requires 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[9].

A practicable monochrome sixteen view version of a Cambridge display has been built at the University of Cambridge[10,11,12]. It utilises a high speed CRT, a projection lens, and a ferroelectric liquid crystal shutter element to emulate the light sources and transparent display screen of the ideal version (Figure 2(b)). It is capable of 16 views at 640 × 240 resolution or 8 views at 640 × 480. The use of a CRT has allowed considerable flexibility in the configuration of the display. Table 1 lists all of the current configurations of the display.

Each view in turn is displayed on the CRT. One of the liquid crystal shutters is made transparent in synchronisation with the image display. This directs the light from the CRT to a specific window in the observer's view space. In terms of geometric optics, the projection lens produces an image of the CRT at a plane in free space, where the liquid crystal display would be in the ideal version. 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. The design of the dynamic lens system for the CRT is optically inefficient as it works by obscuring all but one of the fields of view. There are other designs, such as the ideal version, which do not use obscuration and which are more optically efficient, but this CRT based design has the advantage that it can be built from currently available components, as described in the following section.

4. THE CAMBRIDGE DISPLAY ARCHITECTURE

The Cambridge display consists of two major electro-optical components and a number of associated drive electronics (Figure 3). The electro-optics comprise a high brightness, high speed CRT, designed for use in projector televisions and the dynamic optical system made

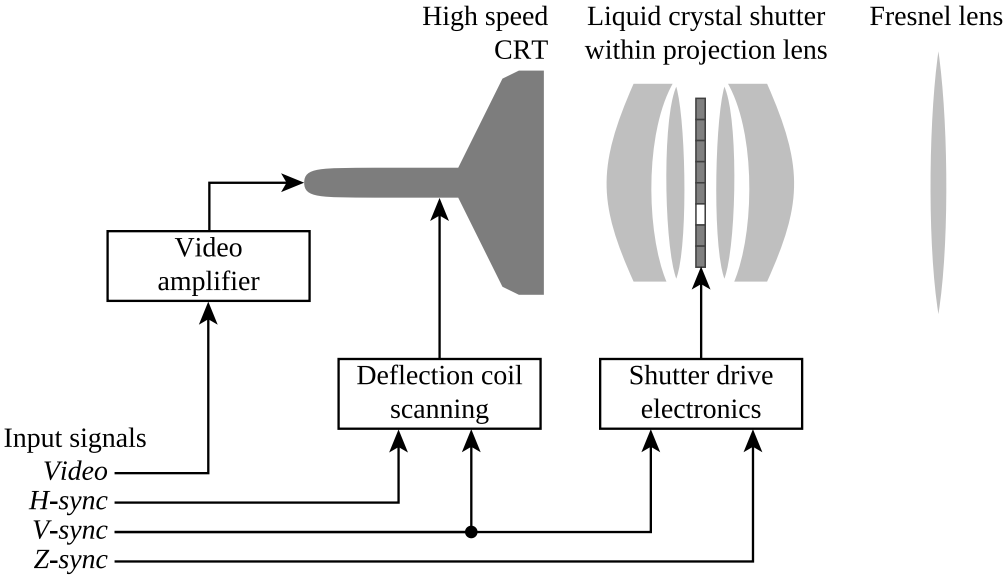

Figure 3: The Cambridge display contains passive optical components (the lenses), active electro-optical components (the CRT and shutter), various drive electronics, and power supply (not shown). Four input signals are required (see Figure 4).

from standard lens elements and the custom liquid crystal shutter. The electronics to drive these are custom circuits designed at Cambridge. The whole system has been assembled and tested at Cambridge.

The CRT is a 9 inch projection tube, with a usable picture area of 160 mm by 120 mm (8 inch diagonal). This CRT is the largest high brightness CRT which was readily available. The phosphor is Zn/CdS P4 white phosphor, chosen for its high sensitivity and fast decay time of approximately 60 μs to 10% of peak light output. It is a combination of yellow and blue phosphors, both with similar decay times.

The dynamic lens system is constructed from a projection television lens, a ferroelectric liquid crystal panel and a fresnel lens:

- The projection lens is 5 inch diameter, the largest readily obtainable. It is made of multiple plastic and glass elements. These were calibrated and their mount was then re-machined to allow for insertion of the liquid crystal shutter.
- The shutter is a ferroelectric liquid crystal element. It consists of a linear array of sixteen segments, each forming a vertical slot. The active area is 100 mm by 100 mm. Each segment is 6.25 mm wide by 100 mm high and switches in less than 100 μs.
- The fresnel lens is a commercially available plastic lens. The image of the CRT forms on a 200 mm by 160 mm area of the lens (10 inch diagonal).

This optical system is relatively simple to construct. There are no critical optical dimensions, apart from the fabrication of the liquid crystal shutter. Even in the shutter, the critical dimensions are well within commercially available liquid crystal manufacturing parameters so that it can be made by a commercial LCD supplier.

The electronics which drive the CRT and the LCD were designed at Cambridge. The CRT electronics consist of horizontal and vertical scan, video amplification, and power supply and CRT protection. The frame rate is between 450 and 1050 Hz, depending on the number of views (see Table 1) and the line rate is 150 kHz. The video amplifier supports up to 150 MHz pixel clock.

The frame and line rates are substantially higher than used in conventional CRT displays. For example, a high specification computer display of 1280 × 1024 pixels would typically have a frame rate of 60 Hz and a line rate of 64 kHz, compared to the 1 kHz and 150 kHz capability of the Cambridge display. The video amplifier bandwidth of 150 MHz is within the performance ability of conventional high specification CRTs. However, to drive the CRT at a high level of brightness requires a 130V peak to peak video signal, leading to peak screen loading of 70 watts. The CRT face plate is liquid cooled. Peak image luminance at the face plate is 34 000 cd/m^2 (10 000 ft/Lambert). Compare this with around 150 ft/Lambert for domestic television.

The electronics for the liquid crystal shutter are relatively straightforward, producing a series of ±40V and ±5V pulses to turn the appropriate liquid crystal segments on and off in synchronisation with the CRT image. Ferroelectric liquid crystals are, however, still in their infancy, and much experimentation was required to determine the voltage pulse timings. The liquid crystal shutter has to be synchronised with the image on the CRT. The shutter is stepped during each vertical retrace of the CRT. It is reset to its initial position by an external *Z-sync* synchronisation pulse.

Several displays have been made to this specification. Half of these have been purchased by external organisations. Of the others, one has since been converted to a prototype 25 inch diagonal display by rearranging the projection lens, and installing a 500 mm by 380 mm fresnel lens.

5. COLOUR

The obvious way to extend the monochromatic version to colour would be to use a three gun shadow mask CRT. This is unfortunately precluded because the high beam current required would destroy the shadow mask. This leaves two options: either three separate red, green and blue display devices, combined with some mirror arrangement, or a colour sequential system using a fast switching colour filter and the fast white CRT already used in the monochrome display.

The first option requires precise alignment of the three display devices and complex combining optics. Neither of these is an insurmountable problem and this solution may be used in the future. In the short term, however, the colour sequential solution has been pursued as being more cost effective. The sole disadvantage of this is that each view direction must be displayed three times: once for red, once for green and once for blue. This reduces the maximum possible view directions from sixteen to six, and decreases the light transmission.

Initial experiments in sequential colour were made using a rotating six segment colour filter (two segments of each primary colour), reminiscent of Baird’s early colour experiments[13]. Rotating at 1500 rpm this provided the first 24-bit full colour autostereoscopic images on the display. However, this mechanical device is unsuitable as a commercial solution, not least because the outer rim of the rotating filter is travelling at 55 mph.

A more suitable mechanism was found in the form of a Tektronix liquid crystal colour shutter[14]. This consists of two consecutive switched liquid crystal colour filters, one switching between red and cyan, the other between blue and yellow. The four possible driving signals thus giving transmission of red, green, blue, and very dark magenta. Drive electronics for this colour shutter were added to those for the directional shutter, and the two shutters abutted within the display.

Observations of the display show that this system gives adequate renditions of all three primary colours. Although the pure red is unsaturated, flesh tones are acceptable, and colour grey-scaling is very good. The red and green are generated from the yellow phosphor component in the CRT, and the blue from the blue phosphor. At peak brightness the display produces 100 cd/m^2 (30 ft/Lambert).

The maximum resolution of this colour display is 640 × 240 pixels, 6 views, 24-bit colour at 50 Hz refresh rate when driven from the computer. A live video system[15] developed at Cambridge can provide six views of full colour video at a resolution of 384 × 288 (half PAL). Any monochromatic Cambridge display can be converted to colour by the addition of a

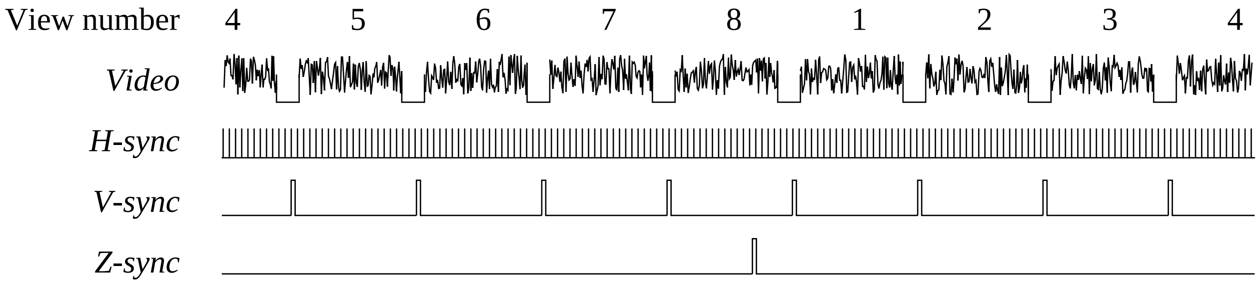

Figure 4: Drive signals for an eight view, non-interlaced, autostereo picture. The views are sent in order, left-most to right-most, one field per view. The Z-sync signal is pulsed during the right-most view. This entire cycle repeats at 60 Hz.

Tektronix shutter and the replacement of the shutter driver circuit board. Four of the extant Cambridge displays are now colour; the remaining monochromatic displays allowing demonstration of both 16 view 640 × 240 images and 8 view full VGA (640 × 480) images. The next development phase is to produce a colour display with higher resolution and more views.

6. IMAGE SOURCES & EXAMPLES

Images can be sent to the autostereo display from two sources at present: a computer or a live video system[15]. The autostereo display takes a standard video signal as input. This signal consists of a single monochrome video channel and separate horizontal and vertical synchronisation channels. All channels are running at the appropriate fast field rate. Each view is sent to the display in a separate field with the views being sent sequentially left to right. This is illustrated in Figure 4. One extra synchronising signal is required on a separate channel. This azimuth sync or *Z-sync* signal tells the display which field represents the left-most view. *Z-sync* consists of a pulse which occurs during the field immediately prior to the left-most view.

The adaptation of conventional video allows any flexible video output system to generate signals for the display. The Cambridge group uses an off-the-shelf graphics card, produced by Datapath, installed in a PC. This card is illustrated in Figure 5. A variety of interactive software has been written for this card to demonstrate the capabilities of the Cambridge display. The majority of this software is built on top of a graphics programming library written at Cambridge, which handles all of the autostereo image generation, leaving the programmer free to concentrate on his or her application program.

Software has also been written for displaying pre-rendered autostereo images and animated sequences of images. A variety of interested parties have provided sets of such images which range from scientific and medical visualisations to video game scenes.

The autostereoscopic camera system, also developed at Cambridge, produces live autostereo video for the display[15]. This system multiplexes input from six (colour) or eight (monochrome) cameras and produces a video stream and synchronisation signals for the display.

Figure 6(a) shows the current 10 and 25 inch displays. Figures 6(b) and 6(c) show example images, photographed off the display screen.

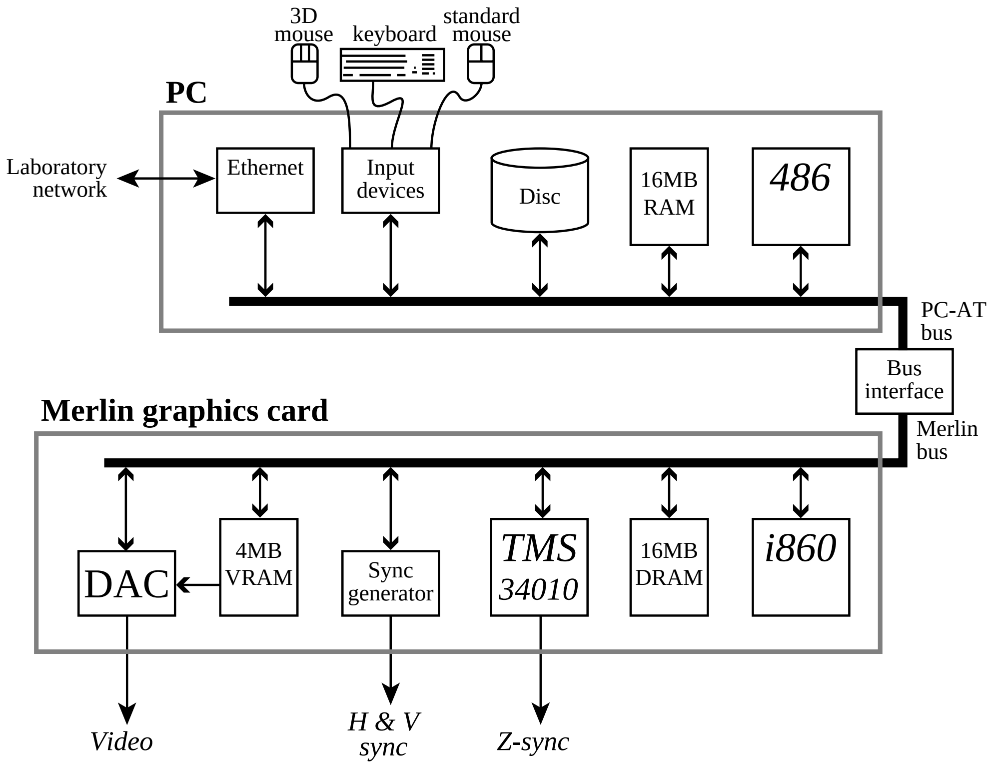

Figure 5: The architecture of the current computer system used to drive the display. The host PC acts as a server for access to disk, input devices, and the network. The i860 on the graphics card is the main processor and performs all of the rendering. The TMS 34010 generates the Z-sync and ensures that the correct field is being output by the DAC at all times. The Merlin graphics card was bought off-the-shelf, but any suitably flexible graphics system could be used to drive the display.

7. THE FUTURE

Current research work is developing a 15 view 400 × 300 pixel full colour autostereo display with a 25 inch diagonal screen. Estimates are that CRT technology can be extended to provide up to 16 views at full VGA resolution from a single CRT tube. Beyond this other display technologies need to be investigated. Currently Cambridge and its industrial partners are investigating various types of fast liquid crystal display devices.

8. SUMMARY

A full colour six view autostereoscopic display has been successfully developed from an earlier sixteen view monochromatic display. This display is in the process of being commercialised, and the first products are expected on the market shortly.

9. REFERENCES

[1] H. Isono, M. Yasuda, D. Takemori, H. Kanayama, C. Yamada and K. Chiba, “50-inch autostereoscopic full-color 3-D TV display system”, *Proc. SPIE*, **1669**, 176–185 (1992)

[2] T. Okosi, *Three-Dimensional Imaging Techniques,* Academic Press (1976)

[3] G. R. Little, S. C. Gustafson and V. E. Nikolaou, “Multiperspective autostereoscopic display”, *Proc. SPIE*, **2219**, 388–394 (1994)

[4] P. St-Hilaire, S. A. Benton, M. Lucente and P. M. Hubel, “Color images with the MIT holographic video display”, *Proc. SPIE*, **1667**, 73–84 (1992)

[5] M. Lucente and T. A. Galyean, “Rendering interactive holographic images”, *Computer Graphics (Proc. SIGGRAPH)*, 387–394 (1995)

[6] W. J. A. M. Hartmann and H. M. J. Hikspoors, “Three-dimensional TV with cordless FLC spectacles”, *Information Display*, **3**(9) (1987)

[7] A. R. L. Travis, “Autostereoscopic 3-D display”, *Applied Optics*, **29**(29), 4341–4342 (1990)

[8] N. A. Dodgson, “Analysis of the viewing zone of the Cambridge autostereoscopic display”, *Applied Optics*, in press (1996)

[9] A. R. L. Travis and S. R. Lang, “The design and evaluation of a CRT-based autostereoscopic 3-D display”, *Proc. SID*, **32**(4), 279–283 (1991)

[10] S. R. Lang, A. R. L. Travis, O. M. Castle and J. R. Moore, “A 2nd generation autostereoscopic 3-D display”, in *Seventh Eurographics Workshop on Graphics Hardware*, 5–6 Sep, 1992, Cambridge, UK, P. F. Lister (editor), Eurographics, Technical Report EG92 HW, 53–63 (1992)

[11] J. R. Moore, A. R. L. Travis, S. R. Lang, and O. M. Castle, “The implementation of a multi-view autostereoscopic display”, in *IEE Colloquium on Stereoscopic Television*, 15 Oct, 1992, IEE, London, UK Digest No. 1992/173, 4/1–4/16 (1992)

[12] A. R. L. Travis, S. R. Lang, J. R. Moore, and N. A. Dodgson, “Time-manipulated three-dimensional video”, *Proc. SID*, in press (1996)

[13] V. K. Zworykin and G. A. Morton, *Television, the Electronics of Image Transmission in Color and Monochrome*, second edition, Wiley (1954)

[14] P. Bos, T. Buzak and R. Vatne, “A full-color field-sequential color display”, *Proc. SID*, **26**(2) (1985)

[15] N. A. Dodgson and J. R. Moore, “Design and implementation of an autostereoscopic camera system”, in preparation