A 2nd generation autostereoscopic 3-D display

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1.1 Introduction

A useful and practical autostereoscopic 3-D display has been developed from an earlier experimental design which was demonstrated in 1990 [8]. The concept of the new autostereo display is unchanged from the earlier one. The use of commercially available components and purpose designed electronics, however, has meant we now have a practical and reliable autostereoscopic display to work with.

We are manufacturing a small number of the autostereoscopic displays for research workers investigating applications of autostereoscopy. Various new applications are being developed here in Cambridge using these autostereo displays, transforming autostereo from a novelty item into a useful tool. In turn the displays requirements are beginning to drive other computer and network system design issues.

This paper gives a brief primer of technologies of autostereopsis, discusses the hardware architecture of the display and its associated computer, describes the software controlling the display and lists some applications. Other state-of-the-art papers [7] [5] [6] consider some of the computer and network system design issues and broader opportunities being opened up by this new display technology.

1.2 Stereopsis — a primer

The elementary cues and effects of 3-D perception can be analysed and described in terms of numerous 2-D images, a given pair of which the human eye pair sees at any one time, and a sequence of which the eye pair sees as the head is moved about. The physiological basis of this relies on the retina of the eye being a 2-D array of rod and cone receptors. A pair of eyes can be focused and directed onto a common object by the eyes' lenses and muscles. The disparity in the resulting 2-D images in the two eyes, combined with the eyes' focusing requirements, is used to fuse a 3-D image in the mind of the observer — "stereopis". Further cues can be found by moving the head slightly — "look-around viewing".

1.3 Autostereopsis

The requirement for stereopsis is for a different 2-D image in each eye of an observer, the images being a stereo pair in correct left-right arrangement.

For autostereoscopy, the observer must see a stereo image:

- without special eyeglasses
- with normal daylight
- with "look-around" viewing — ie multiple views

- with video rate updating — 25 Hz

With the exception of the video rate updating, the requirements for the image's attributes listed above can be explained by comparison with photographic colour holograms. The video rate updating is self-evidently the motion picture effect achieved by television. Accordingly, we will not expand here on these necessary attributes.

We will point out, however, that the "look around" viewing can usefully be limited to horizontal movement — humans are most sensitive to lateral disparity as the human eye pair is laterally displaced. We will rely on this anatomical detail to consider only horizontal disparity from now on.

1.4 Overview of autostereo technologies

There are various ways of creating an autostereo pair of images in an observer's eyes. The practical methods that meet the necessary attributes fall in to three categories: hologram displays, spatially multiplexed displays and time multiplexed displays.

1.4.1 Hologram displays

Hologram displays [1] are the conceptual ideal, but need laser light and precision optics. This method uses a display of optic wavelength pixel resolution. Presently, these are restricted to a single line and so also need a spinning mirror to scan in the vertical direction.

The benefit of the method is that it offers true 3-D. The disadvantage is that the images are small size and that enormous bandwidth is required. Further, the present apparatus needs to be relatively massive to maintain alignment. There is little evidence that these limitations will alter in the near future, so it is unlikely we will see practical dynamic holograms in the foreseeable future.

1.4.2 Spatially multiplexed displays

Spatially multiplexed displays [4] are popular and simple, the most common being the lenticular display; another is the barrier strip. This method uses a conventional CRT or LCD screen to display multiple 2-D views of a scene and a faceplate lens to present each view in a different direction.

The benefit of this method is that it can use readily available CRT or LCD displays. The limitation is that the resolution of the CRT or LCD is divided equally amongst each of the 2-D views. Thus a CRT with 1024 horizontal resolution can only show a 3-D scene of 2 views with 512 horizontal resolution, and so on.

1.4.3 Time multiplexed displays

Time multiplexed displays [2] are a relatively new concept in autostereo displays. This method uses a a high frame rate CRT or LCD to display the multiple views in rapid succession and a dynamic lens system to change the angle of view of each frame.

The benefit of this method is that the CRT or LCD resolution is only that of a single 2-D view, thus a CRT with a resolution of 512 can show 3-D scenes of 512 resolution. In addition, the lens path is co-linear for all views, making for simple optical alignment. The CRT has to go faster than normal of course, for instance needing to be 8 times conventional frame rate to show an 8 view 3-D scene. However, increased speed of displays is usually easier to obtain than increased resolution. The other limitation is that the dynamic lens must be fast and good enough to prevent cross-talk (ghosting) between views. Such lenses can now be made.

1.5 Physics of the 3-D technology we use

The autostereoscopic 3-D display we have developed [8] is a time multiplexed display. It uses a CRT to create each 2-D image and a dynamic lens to direct the image on the CRT to a specific narrow arc within the lens field of view. The dynamic lens comprises a pair of lenses and a movable slit. Its operation may be explained either in terms of optical Fourier transforms, or in terms of geometrical optics. See Figure 1.1.

In terms of optical Fourier transforms, the first lens Fourier transforms the CRT image, then the second lens inverse Fourier transforms it to reproduce the original CRT image. The Fourier transform of the CRT image lies in the focal plane of the second lens. The movable slit is placed in this plane. Since position in the Fourier plane transforms to direction in the spatial plane, the image of the CRT becomes visible from a single arc of viewing angles.

In terms of geometric optics, the first lens produces an image of the CRT at a plane in free space. The second lens is placed at this plane, so that an image of the CRT appears to lie on the surface of the second lens. The movable slit is then placed in the focal plane of the second lens. All light passing through a single point in the focal plane of a lens is collimated by that lens into a single direction. So the action of the slit placed in the focal plane of the second lens is to make light which forms the CRT image on the second lens leave it in a single general direction. So the CRT image becomes visible from a single general direction.

The direction from which the CRT image is visible can be controlled by changing the slit position. The correct view is delivered to each of the observer's eyes by displaying the appropriate image in synchronisation with the change in slit position. It then remains merely to repeat this frequently enough for a stable image to be formed for the observer to achieve stereopsis and complete the 3-D illusion.

The slit device is square because this gives the most efficient use of lens size. Each slit is rectangular, its width being $1/n$ of its height, where n is the number of 2-D views in the 3-D scene. The slit moves only in the horizontal plane as we only support lateral stereopsis.

The design of the dynamic lens is optically inefficient as it works by obscuring all but one of the field of views. There are other designs which do not use obscuration, and which can be more optically efficient. We chose to use obscuration as we knew we could obtain proven optical components for these optics.

1.6 The 3-D display architecture

The 3-D Autostereoscopic Display consists of 2 major electro-optical components and a number of associated drive electronics — see Figure 1.2. The electro-optics are a high brightness CRT, made for projector TVs, and the dynamic lens made from both standard and custom elements, which we designed and assembled ourselves. The electronics are custom circuits which we also designed and assembled ourselves.

The CRT is a 9" projection tube, with a usable picture area of 16 cm by 12 cm, or 20 cm diagonal. This is about A5 paper size, or a half of an A4 sheet of paper. The phosphor is blue. We chose this CRT as being the largest high brightness CRT which is readily available, and the phosphor as being suitable for a high frame rate display.

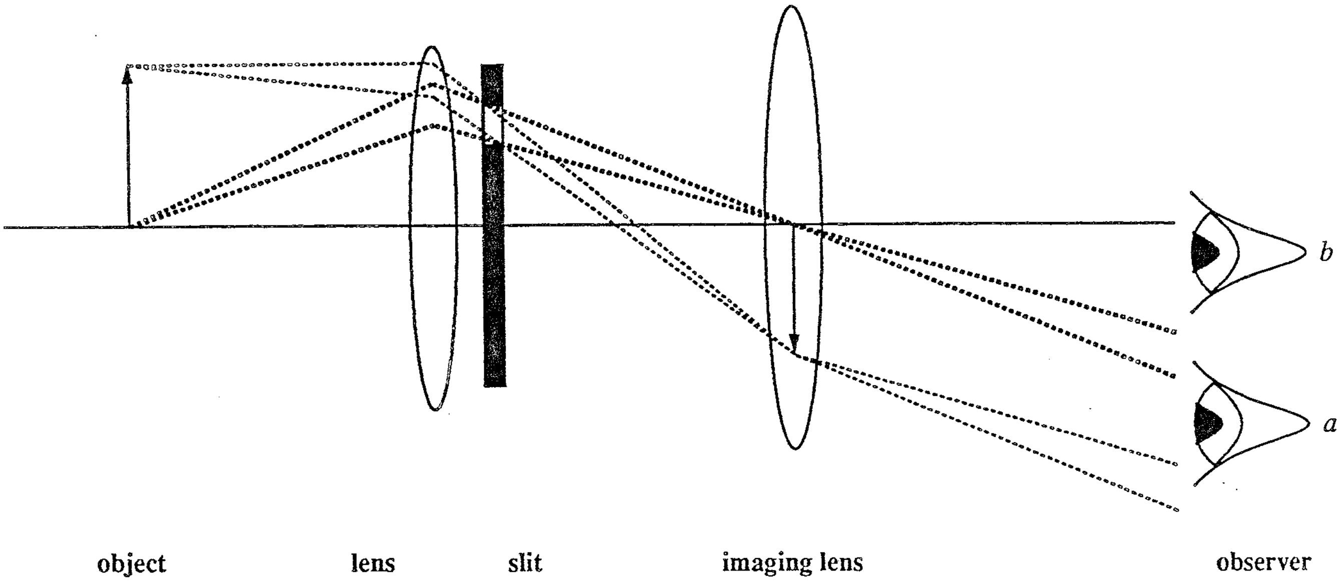

FIGURE 1.1. Dynamic lens: logical operation. An image of the object is formed on the second lens by the first. The position of the slit determines the direction from which this image can be seen by the observer; in the position shown, only observer *a* sees an image of the object, while observer *b* sees nothing.

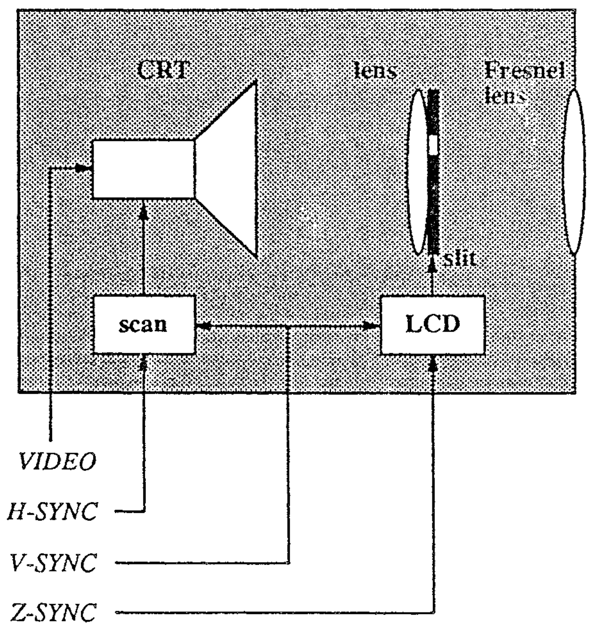

FIGURE 1.2. Autostereo display: block diagram

The dynamic lens is constructed from projection TV lenses, a ferro-electric LCD panel and a Fresnel lens:

The projection lens is 5" diameter, the largest we could readily obtain. It is made of multiple plastic and glass elements which we calibrated, and then re-machined their mount to insert our LCD shutter at the Fourier plane.

The shutter is a ferro-electric LCD, and consists of a linear array of 16 segments, each forming a vertical slit. The active area is 10 cm square. Each segment is 0.625 by 10 cm and driven directly.

The Fresnel lens is the same size as the image on the CRT faceplate and is a commercially available plastic lens.

A property of this dynamic lens is that it is relatively simple to construct, with no critical optical dimensions, apart from the fabrication of the LCD. Even in the LCD, the critical dimensions are well within commercially available LCD manufacturing parameters so that it can be made by a commercial LCD supplier.

The electronics which drive the CRT and the LCD were designed by us. The CRT electronics consists of horizontal and vertical scan, video amplification, and power supply and CRT protection. The frame rate is either 1kHz or 500 Hz, depending on the number of views — (see Section 1.8 for parameters) 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 by 1024 pixels would typically have a frame rate of 60 Hz and a line rate of 64 kHz, compared to the 1kHz and 150 kHz we needed. The video amplifier bandwidth of 150 MHz is within conventional high specification CRTs. However to drive the CRT a high level of brightness requires a ±130V peak to peak video signal, leading to peak screen loadings of 70 watts. The CRT faceplate is liquid cooled.

For the LCD, the electronics was relatively straight forward, producing a series of ±40V and ±5V pulses to turn the appropriate LCD segments on and off in synchronisation with the CRT image at approximately 1kHz repetition rate. Ferro-electric liquid crystals are still in their infancy, however, and a lot of experimenting was needed to determine the voltage pulse timings.

The LCD shutter has to be synchronised with the image on the CRT. The shutter is stepped during each vertical re-trace of the CRT. It is reset to its initial position by an external synchronisation pulse.

1.7 Computer graphics system architecture

The autostereo display is driven by a video protocol consisting of a sequence of conventional 2-D video images, and an additional synchronisation signal at the start of each sequence. The sequence can be either 8 or 16 images, depending on the application. Details of resolution are given in the next section. The timing diagram for the 8 image video protocol is shown in Figure 1.3.

To meet the protocol, a computer graphics system has to output the images in the correct order with H, V & Z-syncs. It has to refresh the whole sequence at approximately 60 Hz, or 30 Hz if interlace is used. As usual, to prevent jerkiness in motion pictures it has to update all images in the sequence at about 25 Hz.

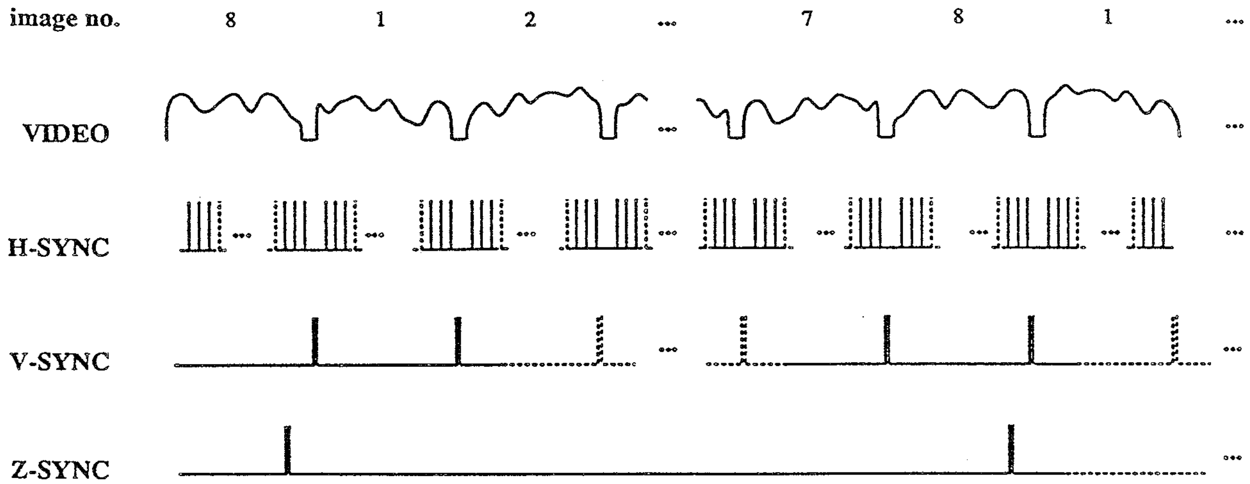

FIGURE 1.3. Autostereo display: video timing diagram — 8 image format

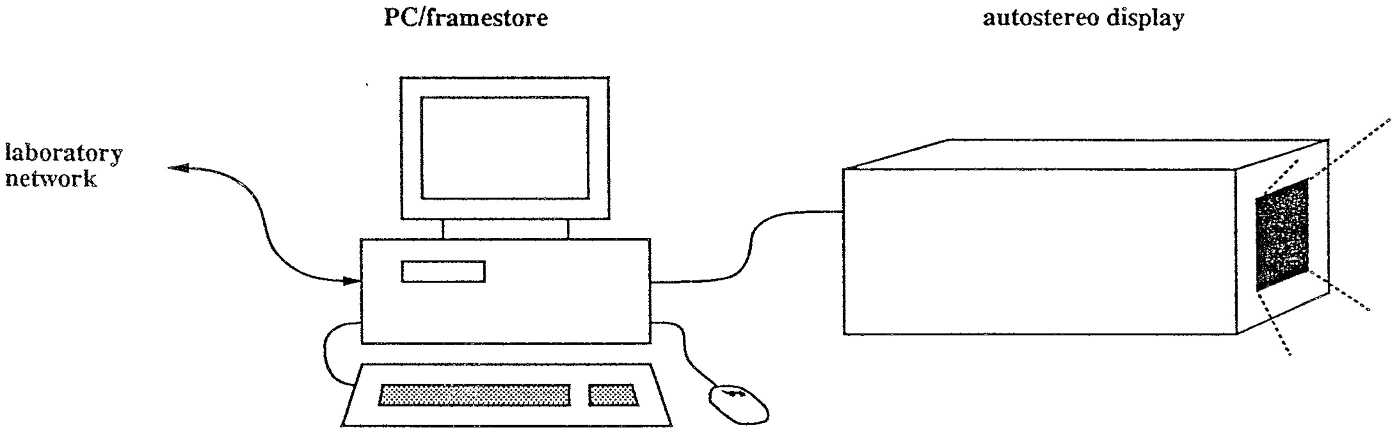

FIGURE 1.4. Autostereo display system configuration

The autostereo display is intended to be driven from a wide variety of video sources which produce the autostereo video protocol. From the outset, we decided we wanted to use conventional computer graphics systems and great care has been taken to make the autostereo protocol a simple extension of conventional video.

For system development, we wanted a framestore with a pixel clock of up to 150 MHz, about 16 Mbyte of memory, a graphics processor and a raster controller which was easily programmable by software.

We found the most flexible and commercially available framestores are designed to work with the IBM PC/AT bus structure running under MS-DOS. We looked at various other configurations, including UNIX, but concluded that the simplicity of a PC with DOS was appropriate for initial experimental work. Now that we have a stable hardware design, we expect most of the autostereo displays to be driven from UNIX systems in the Laboratory. The overall configuration of the system used in our development is shown in Figure 1.4.

We selected a framestore with an Intel i860 processor, a TMS 34010 raster controller, 16 Mbyte DRAM and 4 Mbyte VRAM. The 860 runs at 40 MHz, and the 34010 pixel clock at up to 225 MHz, which generously exceeds our range. The framestore board is a Merlin, made by Datapath [3].

For a host processor to the framestore, we selected an IBM PC/AT clone with an Intel

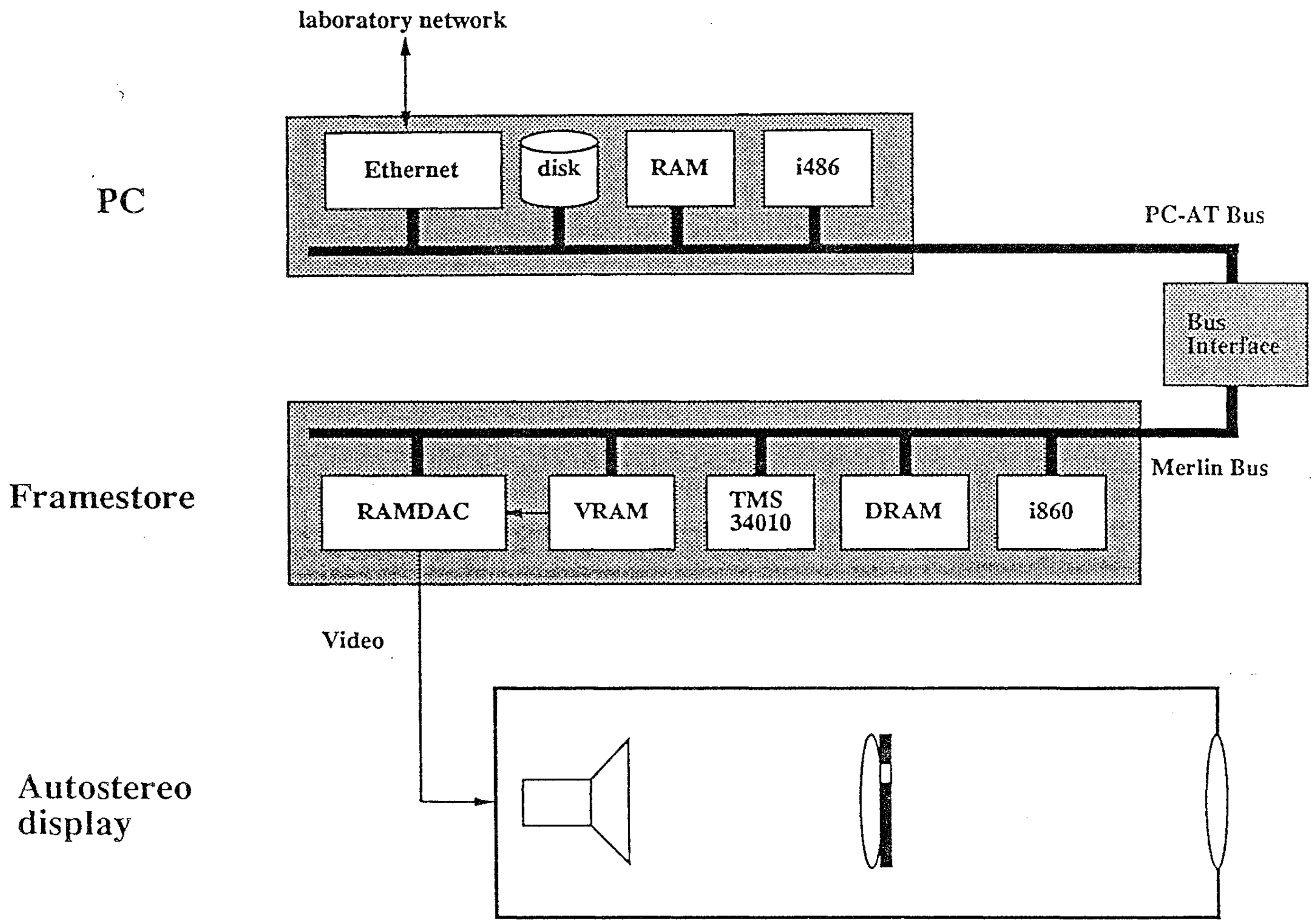

FIGURE 1.5. Autostereo display system: block diagram

486 at 33 MHz, 4 Mbyte of RAM, 110 Mbyte hard disc and an Ethernet interface, plus the usual VGA screen, keyboard and mouse. A block diagram of the system is given in Figure 1.5.

1.8 3D image parameters

The autostereo display is limited by two critical parameters: the angle of view per view and the line rate of the CRT.

The angle of view per view is a critical measure as it controls the horizontal space within which an image on the CRT is visible to the observer at a given distance. That space must be less than the human inter-ocular distance of approximately 65 mm so as to ensure the different view in each eye required for stereopsis at all points in the total view space.

For an observer at one meter from the display, a 1 degree angle of view gives a horizontal view space of 17.5 mm, or 3.7 views per inter-ocular distance. An observer closer to the display will have more views per inter-ocular distance and vice versa.

The maximum line rate of the autostereo display's CRT is a critical measure as it is the limiting factor on the vertical resolution of each image in the sequence of images on the CRT.

Resolution	No. of views	Interlace	Field rate	Line rate	Pixel rate
320 × 240	8	non-interlaced	480Hz	150kHz	72MHz
320 × 240	16	interlaced	960Hz	150kHz	72MHz
640 × 480	8	interlaced	480Hz	150kHz	144MHz

TABLE 1.1. Autostereo display formats

The CRT system we designed has a line rate of 150 kHz. At VGA resolution of 640 by 480, this means it can show a sequence of 8 images, interlaced. At half VGA resolution, 320 by 240, it can show 16 images interlaced or 8 non-interlaced. This is summarised in Table 1.1.

The pixels are monochrome blue with 256 levels of grey scale.

The angle of view per view is controlled by the LCD shutter in steps of 1 degree per view. We have set the dynamic optical system to give 1 or 2 degrees per view to give approximately 4 or 2 images, respectively, per inter-ocular spacing (65 mm) at a meter from the display. Overall this means a horizontal viewing area of 30 cm at one meter from the display. The autostereo effect continues well beyond the one metre distance and is still visible at several metres from the display.

This whole topic is the subject of a future paper. It seems that that 2 degrees per view is perfectly acceptable at a metre from the display, and 1 degree per view is even better.

1.9 Software issues

A great advantage of this autostereo display is that it uses conventional 2-D images which do not require specialised pre-processing. This means we have been able to use various existing software packages to prepare the 3-D images, both still and moving, synthesised and camera input.

For synthesised images, we developed a pre-processor package to an existing ray-tracer to provide a way of automating the generation of multiple views. The package generates multiple virtual camera positions for each scene and passes them (along with the rest of the scene) on to the raytracer for rendering.

For camera images, we have used existing 2-D image capture and manipulation software packages along with a bank of video cameras. This work is still at the experimental stage.

Other software effort is divided into system level driver development and 3-D application management, with the functions spread across the Intel 860, 486 and TMS 34010.

The driver issues are common with many graphics libraries, the novelty is in managing the multiple views. A requirement on the TMS 34010, for instance, is that the start address for each view it outputs changes on a frame by frame basis, and the Z-sync signal must be generated to indicate the start of each 3-D image to the autostereo display.

1.10 Computer & network system issues

The 3-D images contain more data than comparable TV images of the same resolution and thus storage and transmission bandwidth increases in relation to the number of views that make up the 3-D image. This has meant we have had to re-think the requirements

Resolution	No. of views	Bits per pixel	Image size	Bandwidth at 25Hz update
320 × 240	8	8	0.6 Mbyte	15 Mbyte/s
320 × 240	16	8	1.2 Mbyte	30 Mbyte/s
640 × 480	8	8	2.4 Mbyte	60 Mbyte/s
640 × 480	8	24	7.2 Mbyte	180 Mbyte/s

TABLE 1.2. Autostereo display: sample format bandwidth requirements

Device	Bandwidth
Ethernet	1 Mbyte/s
SCSI Disc	10 Mbyte/s
Cambridge Fast Ring	12 Mbyte/s
DEC Turbo Channel	100 Mbyte/s

TABLE 1.3. Comparative bandwidths (peak figures shown)

and balance of processor and network usage.

Some sample image bandwidth calculations are given in Table 1.2. Comparison with the bandwidth figures given in Table 1.3 suggests that the volume of data involved is such that image compression techniques will need to be used in order to operate the display at sustained TV update rates (25Hz) sourced from current commonly available storage devices and networks. For instance, a SCSI disc cannot cope with even the lowest resolution (320 × 240 × 8 views, 8 bits per pixel) autostereo format at 25Hz update rate uncompressed, yet with (say) a 10:1 compression ratio might manage images of twice the horizontal and vertical resolutions (640 × 480). Full (24-bit) colour images of the same size would demand a much faster device — faster even than the internal peripheral bus on the DEC workstations in our lab — or even higher compression ratios.

We have limited ourselves to 8 view 320 × 240 monochrome 8-bit images for present application experiments. Initial tests with short sequences of these 3-D images have demonstrated the feasibility of near TV-rate (20Hz) updating from images previously loaded into DRAM from local disc or remote file server sources on the lab's Ethernet network, transferring images from DRAM to VRAM in software only. For more real-time TV-rate updating of 3-D images, it is proposed that hardware better suited to the task of large volume high-speed data transfer is to be employed. This problem is being addressed by current research being undertaken by colleagues in the Computer Laboratory concerning high-speed framestores and networks.

1.11 Future display hardware developments

Higher resolution 3-D images, colour and larger image size are the issues for the future. We believe that LCD panels as the 2-D image source provide a solution to most of these issues. However, we need LC panels with a frame rate at least 8 times that of TV display panels. It appears such panels can be now made and we will be working on this topic with various partners.

Other areas of activity involve real-time image capture from banks of video cameras and their automatic image registration. There are a lot of problems in this field which will be driven by the availability of 3-D autostereo displays.

1.12 Conclusion

Autostereoscopic Displays with a useful specification can now be made using CRT and LCD components. These 3-D displays are opening up new application areas involving depth perception, such as remote imaging and medical imaging, as well as holding much promise in other applications such as scientific visualisation, CAD/CAM and even videophones. In addition, their particular bandwidth requirements are demanding new thinking in a number of computer system areas, including high-speed framestores, storage devices, and communications networks.

1.13 References

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