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Three-dimensional visualization without glasses: a large-screen autostereoscopic display

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ABSTRACT

This paper describes our time-multiplexed 3-D display technology, which allows groups of viewers to see full stereo with kineopsis (lookaround capability) without the use of any eye or head gear. We detail the constructions of our latest 50-inch screen prototype, which is brighter and has higher resolution than our 25-inch prototype presented previously.

The time-multiplexed concept allows the sequential projection of narrow strips of images into the viewer space and provides realistic movement parallax in a horizontal plane with full autostereoscopic images. The time-multiplexed nature allows for full-screen resolution for each view and shared components for the optical trains.

Our latest prototype, configured for entertainment applications, replaces our previous color sequential system with separate red, green and blue CRTs to give a brighter image (up to 120 ft-lamberts) with much better color saturation. A new optical layout uses dichroics and beamsplitters to avoid the need for coatings with sharp cut-off frequencies, and a concave-mirror screen provides better image sharpness. We are also able to provide up two fifteen views in each eyebox without any tube-abutment seams.

Electronic performance has been improved to provide capability of 30 frames-per-seconds interlaced at 640 by 480 pixel resolution. Special picture-shape correction circuitry has been added to provide a rectangular image-frame, despite a light path skewed out-of-plane.

Our prototype consists of two optical channels, which share the same viewing screen and allow two groups of observers to see completely different 3-D scenes simultaneously. Initially configured as a pre-production prototype for the location-based entertainment marketplace, this layout may have novel applications in the military arena.

Key words: autostereoscopic, stereopsis, 3-D display, lookaround, kineopsis

1. INTRODUCTION

We discuss our head-gear free, autostereoscopic technology and describe the design and fabrication of a new large-screen version with enhanced features. Previously we have reported a variety of prototypes culminating in a 25-inch diagonal screen version aimed at the arcade-game market. Our latest device doubles the screen dimension to 50 inches, is capable of higher resolutions and gives better picture clarity.

The new system uses a concave mirror as a screen, rather than a Fresnel lens, to allow for larger dimensions, and replaces the color-sequential shutter system with separate red, green and blue (RGB) cathode-ray tubes (CRTs). We have redesigned the optics to accommodate these modifications and to remove some visual artifacts present in some of our earlier versions.

The new optics and improved electronics drive circuitry have allowed us to achieve a 640 by 480 pixel resolution at a 30 Hz (60 fields per second, interlace) frame rate for each of the 15 camera views output by each channel in the system. Image brightness goes up to around 100 foot-Lamberts, primarily because of the RGB CRT system, allowing easy viewing under normal indoor lighting conditions.

The new-system specifications have been driven by marketing research in the location-based entertainment arena and also with a view to developing applications for command and control uses in the aerospace industry. The complete 50-inch prototype provides two separate 3D viewing cross-sections (eyeboxes) about a foot square, separated so that two observers may be positioned side-by-side and view different images on the same 50 inch screen simultaneously. As such we have configured it with two side-by-side independent optical channels with off-axis light paths. Picture-shape correcting electronics allows for distortion-free rectangular images in a 4:3 format.

2. BACKGROUND

The original concept for the time-multiplexed 3D technology was developed over a decade ago in the Engineering Department at the University of Cambridge, England and derived from work with liquid-crystal switching technology. The initial configuration (refs 1 and 2) involved a high-speed liquid-crystal display (LCD) illuminated by a series of abutted vertical light bars operating sequentially. Early limitations on the speed of LCDs shifted emphasis to an alternative configuration based on CRT-based imaging also patented in ref 1. These ideas were developed in the early 1990s in Cambridge by a start-up company (now ASD Systems), with additional funding from a Los Angeles-based entertainment company (Infinity Multimedia in Sherman Oaks) with a view to applications in the location-based entertainment and display-kiosk marketplace. This effort was later joined in the mid 1990s by Litton Industries, which provided engineering expertise and funding for the 25-inch and 50-inch prototypes, in exchange for rights to the aerospace market.

2.1. LCD-panel layout

Figure 1 below shows a top view of the basic layout of an idealized time-multiplexed system. A fast LCD is illuminated by a series of abutted light bars mounted a distance back from the display. A Fresnel lens is mounted at the plane of the liquid crystal and spacings adjusted so that real images of the light bars are formed in a horizontal row in front of the LCD at the normal viewing plane. Thus a single energized light bar will produce a narrow vertical slit of light focussed at the viewing plane. In this case, an illuminated image will be seen on the LCD only if the viewer's eye lies within this narrow vertical slit of light. By sequentially turning on and off the vertical light bars and appropriately synchronizing images on the LCD, a series of different images can be projected in turn across the vertical slices making up the viewing plane. If these slits are narrower than the eye separation, then each eye will receive a different image. By sequencing images representing different camera views of a scene fast enough to take advantage

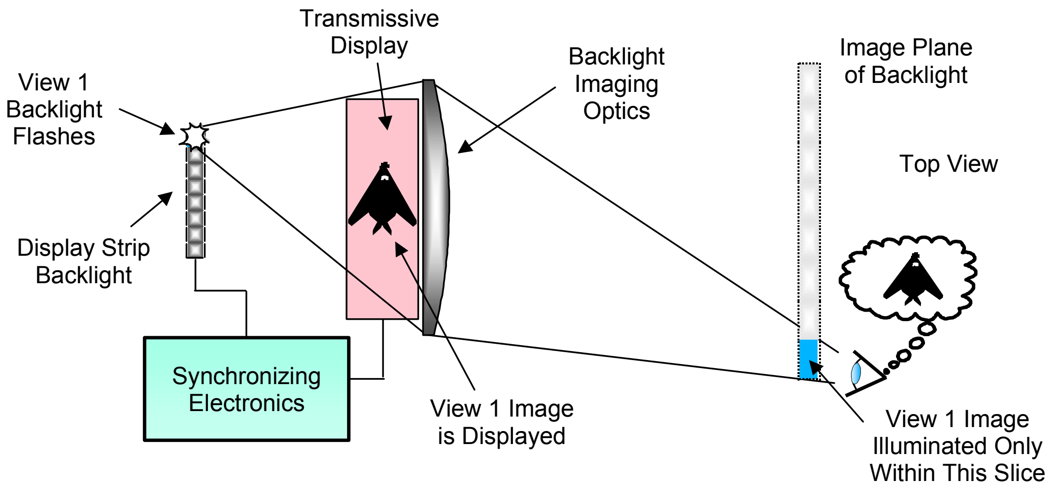

Figure 1: Idealized time-multiplexed 3D display layout. The illuminating source is separated from the image-generating plane and can be manipulated to direct time-sequenced images into the appropriate spot in the viewer's plane of view.

of the persistence of vision, we can create true stereopsis in the brain and a perceived 3D image; this is the time-multiplexed approach. Moreover, for multiple vertical slices containing the correct camera-angle views, the observer will perceive kineopsis, or lookaround capability with horizontal head movement. 3D imagery is seen as long as the viewer's eyes lie within the eyebox cross-section defined by the real images of the light bars. In practice this eyebox can have considerable depth, meaning that the viewer is free to move closer and further back from the Fresnel-lens screen without losing the 3D sensation.

2.2. Cathode-ray tube layout

For the time-multiplexed concept to work, the display device must be capable of generating images at a comfortable frame rate for the eye (at least 30 Hz) multiplied by the number of views presented in the eyebox. Presently, nematic LCDs struggle to maintain a reasonable frame rate for a single image and are not feasible candidates for the ideal time-multiplexed configuration. As is examined later, some of the more recent smetic ferroelectric liquid-crystal materials may make this configuration practical, but most of the 3D displays we have developed so far have been based on a layout using faster CRT imaging technology, shown in Figure 2 as a top view. The LCD and backlight bars are replaced by a CRT and a

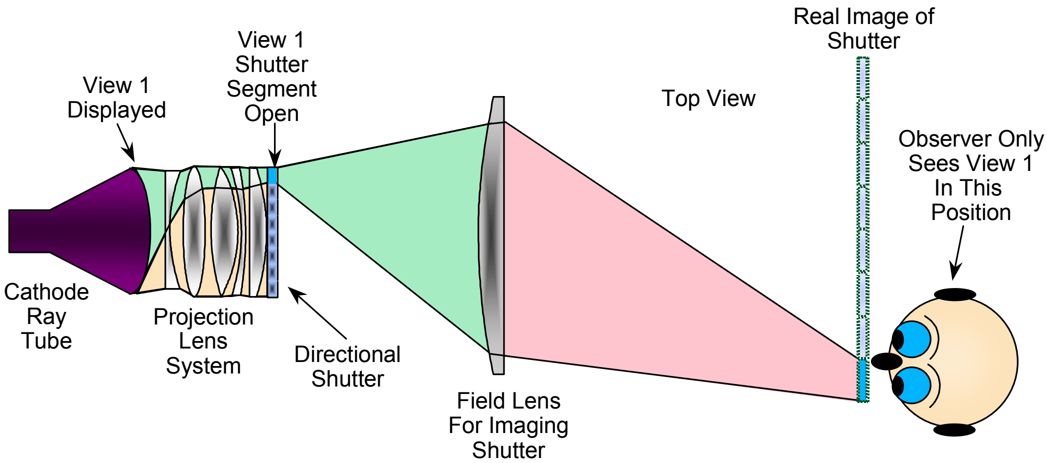

Figure 2: The CRT version of the time-multiplexed concept. Because the illuminating source and the image are both within the phosphor, a directional-shutter device is needed to direct the images into the appropriate places in the viewer's field.

projection lens system containing a fast ferroelectric shutter comprising of a series of vertical segments. A Fresnel lens is placed at the real image of the CRT created by the projection lens system and acts to produce a real image of the shutter elements in the normal viewing plane. In essence this system consists of two optical parts. The first is the CRT and projection lens system and is similar to a rear-projection TV but without a frosted screen in the image plane. The second is the shutter and Fresnel-lens system, which acts to direct the light from the first system into the vertical slices necessary to make the 3D imagery work. However, note that, unlike a rear-projection TV, the imaging plane is not opaque, and the viewing is effectively looking through the window it defines directly at the CRT faceplate, magnified by the Fresnel lens. Since the viewer is not looking at an intermediary image, the optical system is much more abberation-tolerant than a conventional projector system, and the luminance of the scene perceived by the viewer is unaffected by the magnification of the Fresnel system.

As the views representing the various camera angles of a scene are cycled on the CRT faceplate, the ferroelectric shutter segments are sequentially made transparent for the duration of each frame. In this manner the correct view is directed to the appropriate position in the eyebox to produce a realistic 3D scene for the observer. This system is functionally the same as the ideal version described earlier. The CRT and projector lens combination has produced an image plane functioning as the LCD plane of the original layout. In both cases this is where the viewer's eyes will focus, although the convergence of the eyes will change according to the image content and cropping.

2.3. Previous 25" screen full-scale prototype

We have previously reported and demonstrated a prototype display with a 25" diagonal screen designed as a pre-production model for the location-based entertainment marketplace. All the components used were specified to be readily available and mass producible, to make a commercial machine competitive in its intended market. This prototype differed from earlier working models made at Cambridge in that it gave full-color animations viewable in a usable eyebox, 24" wide by about 8" high, on a platform which could be produced in mass quantities. Maximum image resolution is 512 by 384 pixels, limited by the off-the-shelf electronics bandwidth we used, but certainly adequate for arcade games.

Figure 3: Previous 25"-screen prototype incased in an arcade-game-style shell.

We introduced color into this system by using broadband P4 white phosphors and a fast liquid-crystal color shutter, which could be switched to transmit red, green and blue light sequentially at rates above 1 kHz. This field-sequential method for introducing color has the advantage of eliminating color convergence alignment problems, but requires a factor of three increase in the CRT frame rate to accommodate the switching between the color elements in each individual image.

Using standard CRT technology, we were conservatively limited to approximately 7 views per CRT by considerations of phosphor-decay time. This requires a field rate of 1260 Hz for a 30 frames-per-second interlaced refresh rate. Tests with the earlier working models showed that the width of the vertical viewing slices in the observer's plane should be no wider than approximately one inch, giving about three views across the average human face. This provides smooth transitions between the vertical slices as the viewer's head moves from side to side. Thus, to produce the commercially required eyebox of 24" wide, we need at least 24 views for our system. We achieved this by abutting four CRTs together side-by-side, so they could project onto the same 25" Fresnel-lens screen, giving 28 views in a 24" wide eyebox. The abutments produce three dark vertical bands in the observer's field of view, which could be minimized by using some unidirectional diffusing techniques, but not entirely eliminated. The ferroelectric liquid-crystal directional shutter used in this system consisted of a one-piece element with 28 vertical segments. Although expensive to manufacture in small quantities, the projected cost in mass production was within the budget dictated for a cost-competitive 3D display for the entertainment market.

Light throughput of such a system is low because 6/7ths of the shutter aperture per CRT is closed at any given time and the necessary light polarizations through the system further cut light intensity. The overall efficiency is only between 1% and 2%. Thus CRT screen luminances should be between 5000 and 10,000 ft-Lamberts to give reasonable image light levels for viewing under normal lighting conditions. These levels are readily available commercially in the white CRT tubes used for projection TVs, but are too high for the implementation of shadow-mask techniques to produce color. Final luminances on the screen were around 40 ft-Lamberts, about that of a typical computer monitor.

For this prototype we developed a real-time image generating system for demonstrating interactive applications. This was based entirely on readily available computer components (DEC-Alpha-based PCs running Windows NT), because we had no desire to invest effort into creating systems that are improving so rapidly in the consumer marketplace (ref 3).

3. THE NEW 50” SCREEN PROTOTYPE

Our work with the 25” prototype showed there were several areas where we needed to improve performance. Firstly, we wanted to increase image brightness and clarity, compromised to some extent by the Fresnel-lens screen. Secondly, we wanted to remove the seams in the visual field produced by the CRT abutments. Thirdly, we wanted richer colors and higher image resolution. In addition, the ever-changing location based entertainment market now dictates a larger screen size as well as the higher resolution and separate eyeboxes for a two-player platform. The aerospace market requires even higher resolutions and large screens for command-and-control type applications.

3.1. Optical system

The basis for most of these improvements lies in the optical layout. Even though this 3D technology may be regarded as a type of rear-view projection system, increasing the screen size is not simply a matter of changing the projector lens set. The laws of physical optics stipulate certain relationships between screen size, viewing distance (which relates to the observer’s effective field of view) and the size of the eyebox. Improving any one of these parameters without the detriment of the others generally means larger-aperture optics.

These are some of the parameters for our earlier 25” display.

Screen size:	25” diagonal
Eyebox size:	7” horizontally for each of four CRTs (total 28”), about 8” vertically
Viewing distance:	60” from the screen
CRT faceplate size:	4” diagonal

These are the optical parameters we desired in the new system.

Screen size:	50” diagonal
Eyebox size:	Two eyeboxes, each about a foot square
Viewing distance:	no further than 7ft from the screen
CRT faceplate size:	no larger than 7” diagonal

The precise calculations of the optical light paths for the lens combinations in the 3D display are complicated. However we may apply simple optical principles using f-numbers (defined as the effective focal length divided by the diameter of the entrance pupil of the lens or system) to give good estimates of the range of parameters available.

The output side of the display’s lens system must have the diverging ability to fan out a cone of rays from a point on the viewing screen to fully encompass the eyebox at the desired viewing distance, as shown on the right hand side of Figure 4. Otherwise, the real image formed on the screen will not be visible from everywhere within the eyebox. If the viewing distance is approximated to be equal to the effective focal length of the output side of the system, the corresponding exiting f-number is the ratio of the viewing distance to the eyebox width. Note this number has nothing to do with the screen size and is independent of any Fresnel lens placed at the real-image position, which will leave the image unaffected.

To find the f-number for the input side (that is, for the projection lens system), we note the ratio of image and object distance for the input side must be equal to the system magnification. Thus the effective focal length of the input side must be reduced by the magnification factor, while maintaining the same aperture, as is demonstrated by the geometry of Figure 4. Thus, the f-number on the input side of the optical system is simply the output-side f-number divided by the magnification of the system.

The magnification of the system is defined by the ratio of the desired screen size to that of the CRT faceplate, which should be as small as possible to keep the system bulk down.

For our 25” system the output-side f-number is 60/7 or about 8.6. Using the 4” CRTs we chose, the projector magnification must be 25/4 or 8.25. Thus the projector lens system must have an input f-number of 8.6/8.25 or a little over 1. Such a lens system is certainly practical as we have demonstrated.

The desired parameters for the 50” system make the optics more of a challenge. To accomplish the two eyeboxes required, we decided to use two identical independent optical trains. Thus each train provides a one-foot square eyebox. If we chose an optimum viewing distance of 6.5 feet, then for a one-foot eyebox, the output-side f-number of each system is 6.5. To minimize the needed magnification while keeping the overall bulk of the display down, we chose the largest CRT faceplate dimension we could

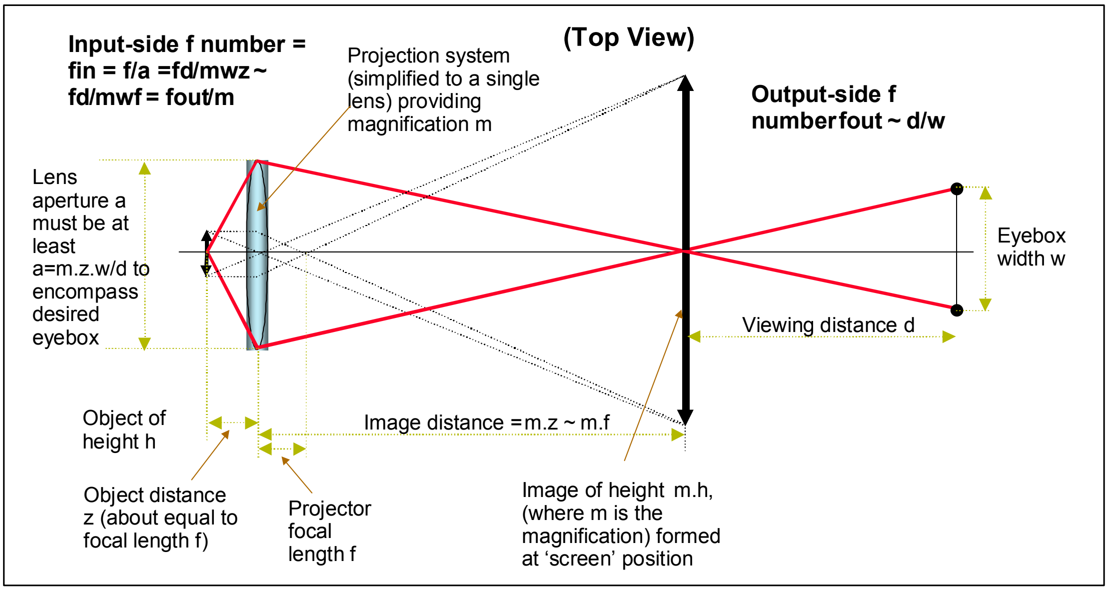

Figure 4: This shows how the projector-lens f-number is governed only by the eyebox width, viewing distance and projector image magnification.

accommodate, 7". Thus the magnification must be 50/7 or about 7.1. This gives us a requirement for a projector system with an input f-number of about 0.9, which is still practical, but not a trivial system to design with good optical clarity.

3.2. Screen options

Our 25" display used a Fresnel lens as the screen, which is lightweight and very cost-effective in bulk quantities. However, the grooves in the surface of such a lens do produce some light scattering and tend to reduce image contrast and clarity. Our 50" prototype would require a much bigger Fresnel lens, which would be much harder to manufacture. Thus we opted for a concave mirror with a simple spherical-section surface as the screen. This had the advantage of superior image clarity and combined the lensing and light folding our geometry would need into one optical element. Geometrical distortions in the image produced by the mirror are corrected by electronic adjustments to raster scan on the CRTs, which are also used to correct for effects from the out-of-plane optical path our dual-optical-train system creates.

3.3. Color

As mentioned earlier, in our 25" system we used a color sequential shutter, which gave no color convergence problems, but required a factor of three increase in the CRT frame rate to produce the three color fields needed in each cycle. As a result this prototype used four CRTs abutted together horizontally and inevitably did shown three faint seams in the field of view. Although we felt we could minimize these further, we opted to design the 50" system with three CRTs, representing red, green and blue, in each optical train and move away from an abutted-CRT design.

The different color fields in the chosen RGB system must be combined at some point in the optical train to be co-axial. We chose to use separate beamsplitting surfaces to achieve this, rather than the crossed surfaces some compact systems use, because of visual artifacts we might see in the field of view from seams along plate joints. Green CRT phosphors are photopically much more efficient than red and blue phosphors, so we could afford to use a neutral 60/40 dielectric beamsplitting surface to fold in the green, wasting 60% of that CRT light. We can now employ a single dichroic surface, which efficiently transmits red and reflects blue light, to combine these two colors with very little loss. This is because, with no green light at this point in the optical train, we can design the dielectric-coating stack to have a broad transition region in the green part of the spectrum. The stack will also exhibit very consistent spectral transmission and reflection characteristics over the wide range of light incident angles we need for our large-aperture optics.

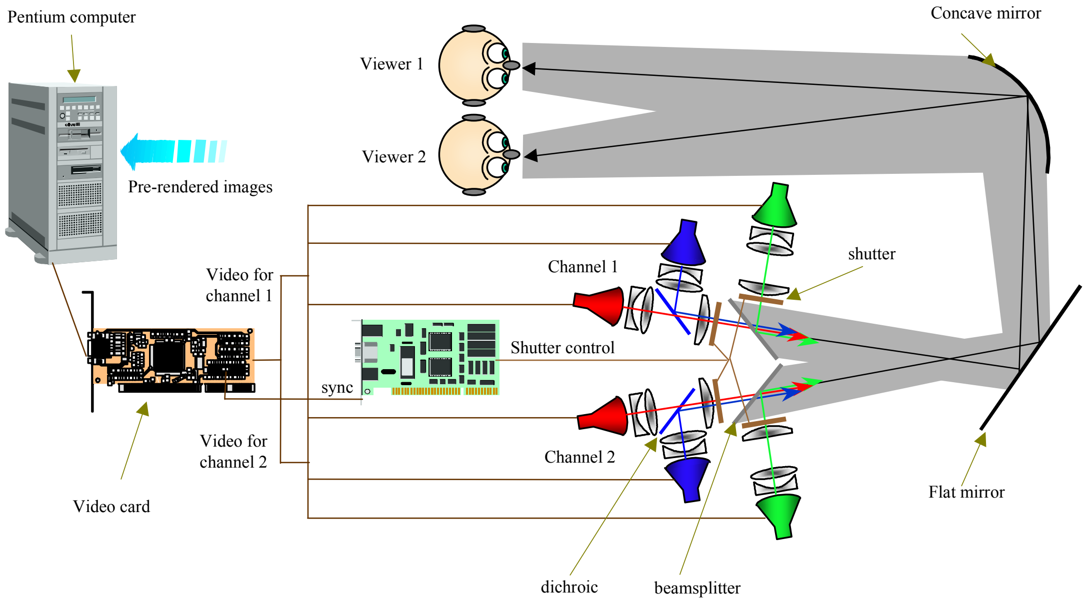

Figure 5: This shows an overview of the layout for the 50” display.

3.4. Overall optical configuration

Figure 5 shows an overview of the optical configuration for the 50” display, with a computer system attached. For our potential marketplace we need a product that has the inner workings below the screen level and a screen position viewed by observers looking forward in either a seated or standing position. This is the configuration preferable for most location-based entertainment and other applications. Another particular requirement of our prototype was that it could easily be broken down to fit through doorways as narrow as 22 inches. The paths from the two optical trains cross so that the viewer on the left side sees images produced by the CRT system on the right side of the display unit and vice versa. The resulting optical path creates an image rotation of the shutter image, so that as the viewer moves back and forth through the optimum viewing plane, although largely unnoticed, this image rotates by ninety degrees. Of course, the image on the CRT screens does not rotate and this effect does not adversely affect the 3D sensation.

3.5. Optical design and fabrication

The detailed lens system was designed for by us Optical Research Associates in Pasadena, California, using Code V software. The optical channel for each color consists of only three rectangular lenses, which have several aspheric surfaces to optimize image quality. With some shared lenses between colors, there are a total of 16 lenses in the complete display unit. The lens material is acrylic, which limits the refractive indices available for design, but in our case this is more than made up for by the ability to use non-spherical surfaces.

The lenses are cut from acrylic blanks approximately 14” in diameter and were handily turned on large diamond lathes by one of the few places we could find to fabricate such large pieces, OFC of Keene in New Hampshire. While these lenses are not practical for a mass-producible display, they are very effective in our prototype and produce images of very good clarity.

The optical components are mounted in sturdy matte-anodized aluminum housings, carefully positioned to give good optical alignment and minimize color-convergence problems. Figure 6 shows a photograph of the lenses for the blue and red light along with the dichroic plate used to combine them into one beam. Figure 8 shows a view of the display being set up at a demonstration in Tokyo, Japan.

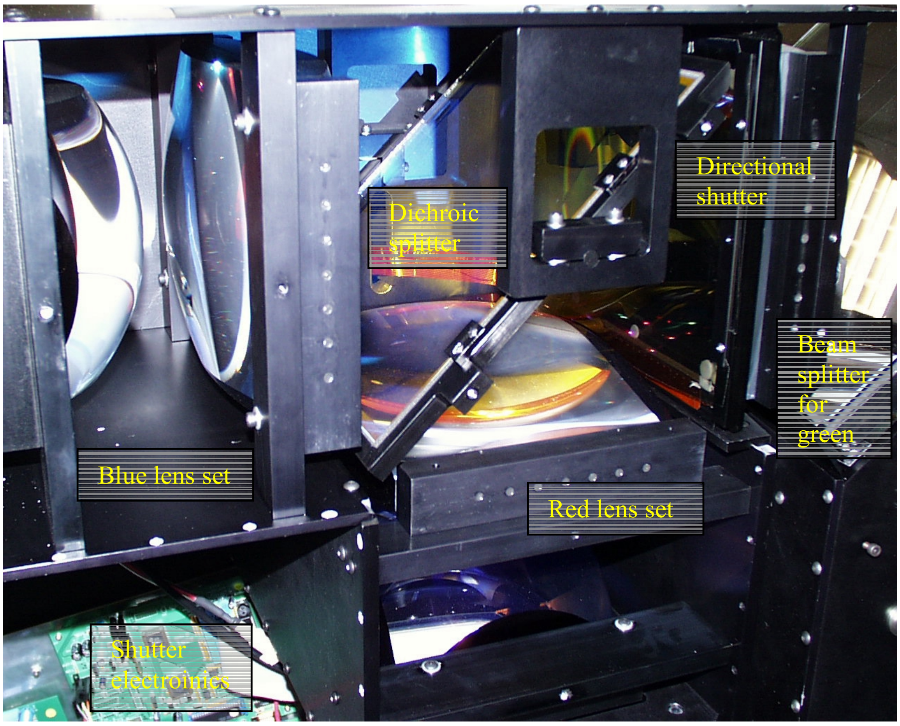

Figure 6: Close-up of one of the opened optical boxes containing the lenses for the red and blue CRT outputs and the shared directional shutter. The green beam is folded in by the beamsplitter surface on the far right.

3.6 Eyebox views and the drive electronics

The 25" display was configured to run in a color-sequential mode with a total of 28 camera views presented in the 2-foot wide eyebox provided by four CRTs at 512 by 384 pixel resolution and 8-bit-per-color depth. The new 50" system has a total of six CRTs operating in a RGB mode projecting into two one-foot wide eyeboxes. We wish to drive this new system with essentially the same electronic bandwidth but with an increased resolution of full VGA, 640 by 480 pixels. To achieve this goal we opted to chose a maximum of 15 views per one-foot eyebox so that we can still run at a line-scan rate of 285 kHz and use commercially available pixel clocks at around 250 MHz.

Our earlier 25" display produced a relatively distortion-free image without any picture-shape correction circuitry applied to the raster scan, primarily because of its inherently planar optical path. The new display has light paths that move out-of-plane and requires the ability to manipulate the raster scan pattern to remove keystoning and other distortions. The picture in Figure 7 shows the resulting picture on the screen to be very rectilinear.

Figure 7: Actual image on the 50" display screen showing how the picture-shape correction on the raster scan gives a rectilinear image.

3.7. Image-generating computer

For our 25" display, we built up a computer system from readily available consumer parts to provide interactive capability for demonstrating the display. Because our 50" device uses an RGB system, rather than a color-sequential system to provide color, the frame order is different and we cannot transplant the image generator to the new display. Instead we used a Pentium II 300 MHz PC with a Datapath Merlin II video card to play pre-rendered images directly from a half-Gbyte RAM memory. This produces images adequate for demonstration purposes, although the 66 MHz motherboard bus rate is somewhat of a bottleneck. A full-production image-generator design is very much dependent on the particular application and the speed of the components commercially available at the time of the implementation.

4. FUTURE POSSIBILITIES

The prototype displays we have built so far are based on CRT technology and, although bulky, are suitable for use in the designated entertainment markets and possibly for some aerospace applications. The

Figure 8: Adjustments are made to the picture shape by software control on the 50" display for a demonstration in Japan.

next phase in the development of this technology would probably involve the use of flat-panel or micro-displays for display units with much smaller footprints. These would allow egress into the computer-monitor and ultimately consumer-TV marketplaces, as well as accommodating many military and industrial applications. We have not yet done any serious development in these areas but present here some initial ideas on the sort of approaches we might consider.

A desktop-sized 3D display based on the presented technological approach is most likely accomplished using some of the digital micro-displays that are currently being rapidly developed. The most likely implementation might involve returning to the original time-multiplexed configuration, where a series of vertical light bars sequentially switched provides the illumination for an image-generating device. This latter device must clearly be capable of fast frame rates beyond those used in traditional 2D displays. Display products such as Texas Instruments' digital micro-mirror devices (DMDs), Silicon Light Machines' linear grating arrays and ferroelectric liquid-crystal micro-displays (FLCDs), such as those produced by MicroPix in Edinburgh and DisplayTech in Colorado, come to mind for this application,.

In simple configurations, it appears that the DMDs are limited by their input f-number, since the micro-mirrors on the substrate are only able to deflect by +/- 10°, giving an apparent limitation on the input f-number of about 1/tan(20°) or 3, thus limiting the ultimate size of possible 3D eyeboxes with reasonable fields of view. Silicon Light Machines' linear grating array is less well-developed and may suffer similar limitations. FLCDs may offer more promise, although there are other issues beyond the scope of this paper to be considered, particularly as regards addressability of these devices at the required line rates (ref 4).

A desktop application might require something of the order of the following parameters.

Screen size: 15" diagonal (12" horizontally, for 4:3 aspect ratio)

Eyebox size: 10” horizontally, about 8” vertically
Viewing distance: 24” from the screen

Based on the previous simple analysis presented earlier, this would require an output f-number of 24/10 or 2.4. Micro-displays are generally rather small (typically about an inch across) and so need a magnification of about 18 to give a 15” diagonal screen size, which puts the input f-number at 2.4/18 or .13. This would appear impractical, since it would place the micro-display virtually on top of the projector lens. However another approach would be to go back to the abutted display layout and use, for example, five micro-displays abutted in a row, so that each need only provide a 2”-wide eyebox. This would require an input f-number around 0.7, which is much more practical in such a small-aperture system.

Figure 9 shows conceptually how such a layout might work, with Figure 10 showing a detail of the kind of configuration for illumination that might be used for each micro-display. Currently available commercial FLC micro-displays are reflective, rather than transmissive as shown, which would entail some adjustments to this conceptual layout. Figure 11 gives an idea of packaging and dimensions for the FLCD-based 3D desktop monitor.

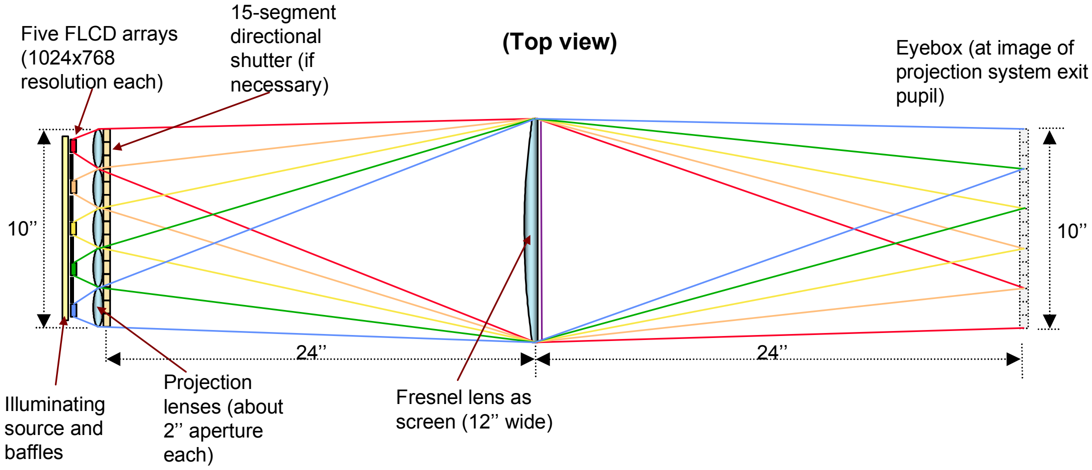

Figure 9: Conceptual optical layout for a 3D desktop display using ferroelectric transmissive micro-displays.

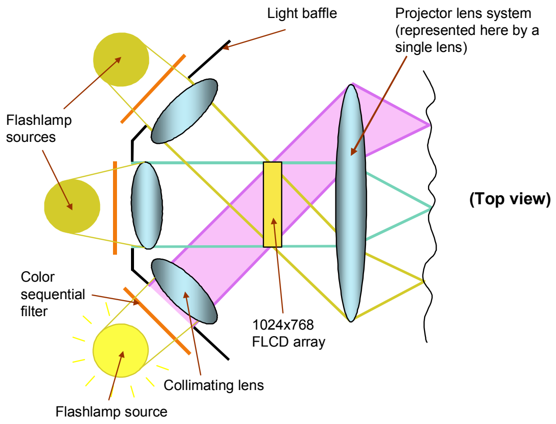

Figure 10: Detail of possible optical configuration for illuminating the FLCDs in Figure 9. This configuration would not require the directional shutter shown there.

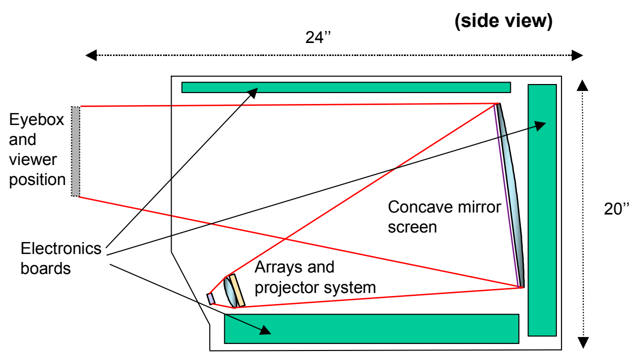

Figure 11: A conceptual layout for a desktop 3D monitor giving approximate case dimensions.

5. SUMMARY

We have presented the latest prototype utilizing our 3D time-multiplexed technology and described the significant improvement it demonstrates over our previous smaller-screen display. We have also described some ideas that may suggest a path for further development of our time-multiplexed 3D technology using flat-panel microdisplays for producing a device with a footprint commensurate with desktop-monitor type applications.

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