Preprint - IS&T/SPIE 17th Annual Symposium - Electronic Imaging Science and Technology, 16-20 Jan 2005
POC: Pat Green, Planar Systems 503 748 6989, pat_green@planar.com

An innovative beamsplitter-based stereoscopic/3D display design

James L. Fergason, Scott D. Robinson, Charles W. McLaughlin, Blake Brown, Adi Abileah, Thomas E. Baker, Patrick J. Green (Planar Systems, Beaverton OR 97006; JLF, CWM and BB, Fergason Patent Properties, Menlo Park CA 94025)

KEYWORDS: 3D display, stereoscopic display, stereo display, AMLCD stereo, stereo beamsplitter, StereoMirror

ABSTRACT

A novel stereoscopic/3D desktop monitor has been developed that combines the output of two active matrix LCDs (AMLCDs) into a stereo image through use of a unique beamsplitter design. This approach, called the StereoMirror™, creates a stereo/3D monitor that retains the full resolution, response time and chromaticity of the component displays. The resultant flicker-free image, when viewed with passive polarizing glasses, provides an unprecedented level of viewing comfort in stereo. The monitor also is bright enough to use in normal office lighting. The display has excellent optical isolation of the two stereo channels and a wide viewing angle suitable for multi-viewer use. This paper describes the architecture of the system and the principal of conservation of polarization that results in the full-definition stereo image. Optical performance results are also described. Practical considerations will be discussed, including system interface requirements, conversion between stereo/3D and monoscopic viewing and comparison to other stereo display approaches. The higher level of performance provided by the StereoMirror™ allows for stereo viewing to be viable in new imaging markets as well as permitting a more effective use of stereo in existing markets. These applications are discussed.

1. INTRODUCTION

While there has been an explosion in the availability of three dimensional and other volumetric imagery in recent years, there has been relatively little progress in the development of commercially viable displays capable of presenting high quality stereoscopic/3D images in high resolution on the desktop. Stereo can provide quicker and more accurate extraction of information and offers a more realistic experience than conventional monoscopic viewing. However, there are several factors that have stifled use of stereoscopic displays to date. These include:

- Discomfort in using stereo displays
- Inconvenience and a limiting "sweet spot" for stereo viewing
- Limited resolution
- Complex computer interface and need for special interfacing S/W

There are two leading types of stereoscopic/3D displays on the market today. One approach makes use of powered liquid crystal shutter eyepieces that present frame-sequential, stereo pair images displayed from a synchronized CRT [1]. The CRT is typically driven at twice the normal video frame rate. A variation of this design places a fast-switching LC shutter in front of a CRT [2]. The LC shutter switches between circular polarization states and the user views stereo using passive glasses. While LC shutter glasses have been a workhorse for a number of years, the powered glasses are bulky and there is potential for flicker in the image and periphery of the field of view. In addition, most any other computer monitor in sight will also appear to flicker from the view through the glasses. This can cause discomfort and thus limit the willingness of the user to make use of stereo. The fast-switching shutter approach limits discomfort from flicker but is quite dim due to the attenuation in the optical path. This system is best used in a reduced ambient illumination. Both of these designs are threatened by the upcoming demise of the CRT. In 2005, LCD monitor sales are predicted to exceed CRT monitor sales for the first time [3].

Current autostereo displays employ AMLCDs and a parallax barrier element created either from a second LC cell or a fixed lenticular lens array [4]. These monitors create virtual stereo pairs of images at roughly the interocular spacing at a fixed distance and location from the screen. The simplest of these designs divides the horizontal resolution of the AMLCD screen in half and directs, for example, the left eye image using the odd-numbered columns and the right eye image using the even-numbered columns. While the user of this design enjoys the benefit of not having to wear glasses to see stereo, they must severely limit their head movement to the "sweet spot" at the convergence point of the stereo image pairs. This point is perpendicular to the center of the screen. Movement outside this zone results in confusing visual artifacts and degraded stereo viewing. More complex multi-domain autostereo screens are available that provide a wider stereo viewing space, but these require starting with higher resolution AMLCD panels and result in a stereo image at a much lower resolution (the resulting resolution is the quotient of the starting panel resolution and the number of domains). Monitors with as many as eight domains have been produced. The graphics card drivers for these autostereo displays are non-standard and complex. The higher the number of domains, the higher the complexity and the greater the computational power needed to manage the stereo image in the graphics card and/or CPU. It is difficult to foresee these displays being available in greater than UXGA (1600x1200) resolution which actually results in no more than 800x1200 resolution reaching the user. These autostereo monitors seem to be well-suited for gaming and advertising applications; however, they are a more difficult fit for professional uses where higher resolution and artifact-free image quality is required.

Conventional active matrix liquid crystal displays (AMLCDs) have desirable characteristics that include excellent image quality, high resolution, flicker-free viewing, ease of computer interfacing and wide viewing angle. To date no desktop stereoscopic display offers all these same attributes. The StereoMirror™ approach to stereoscopic/3D monitors [5] described in this paper combines the output of two active matrix liquid crystal display (AMLCD) monitors into a stereo image using a novel beamsplitter design. This design requires the use of simple polarizing glasses and fully addresses the shortcomings of current approaches in a simple and cost effective manner that provides the aforementioned desirable performance characteristics.

2. STEREOMIRROR™ CONCEPT

A StereoMirror™ monitor, as pictured in Figure 1, consists of two AMLCD displays oriented at a fixed angle (120º in this example) through use of a specially designed mounting stand. A passive beamsplitter mirror bisects the angle formed between the two monitors mounted on the stand. The mirror has the following properties:

- 50% transmission
- 50% reflectance
- Non-birefringent
- Flat spectral response from 400 to 700nm
- Abrasion-resistant hardcoat

An anti-reflective coating is deposited on the side opposite the mirror film to minimize secondary image reflection. There is a fine mechanical adjustment for the mirror angle between the two displays.

The objective of a stereoscopic display is to efficiently present a Left eye image to the Left eye that is isolated from a Right eye image presented to the Right eye. This allows the visual system to merge the two images resulting in the perception of depth, or stereopsis. In the StereoMirror™ design this stereo separation is achieved using the principle of conservation of polarization. Liquid crystal displays operate based on the ability of liquid crystal material to modulate plane-polarized light. The planes of polarization for light emitted from the two AMLCDs in a StereoMirror™ have the same orientation, e.g. 45º, depending on the type of LC cell. The plane of polarization for the image seen in transmission (See Figure 2) from the lower monitor (Left eye image) is unchanged in passing through the mirror. However, the polarization plane in the light path of the upper monitor (Right eye image) is effectively rotated 90° upon reflection.

When stereo pair images from the two monitors are viewed through crossed-polarizing glasses, the user only sees the Left eye image with the eyepiece having the forty five degree-oriented polarizer and the Right eye image with the eyepiece having the 135° polarizer. Images with orthogonal polarization are extinguished. The result is a single, fused stereoscopic image.

A block diagram describing the process of driving a StereoMirror™ monitor is shown in Figure 3. The Left eye and Right eye images are sent to their respective AMLCDs independently and without any special treatment (with the exception of accommodating for the fact that the upper monitor is seen in a mirror – this will be discussed below). Presenting the stereo pair of images is accomplished using a software application predisposed to accommodate dual monitor stereo viewing. This software is typically written to be compatible with either OpenGL [6] or DirectX [7]. It requires no additional modification for use with the StereoMirror™ monitor design. Any software application that uses the OpenGL quad-buffered stereo features is compatible with the StereoMirror™. Quad buffered stereo is a feature of the OpenGL 3D graphics library that allows an application to define two separate Right/Left eye viewpoints instead of the normal single monoscopic viewpoint. The two viewpoints are defined to give the correct parallax separation for the proper stereo effect. Once the two viewpoints have been defined the 3D scene is rendered identically for each of the two viewpoints. Many commercial 3D applications already have stereo viewing modes using the OpenGL stereo features.

Since the upper display in the monitor is seen in reflection there is a need to perform a mirror-flip operation on that data path. This can be accomplished in a number of ways:

- Software processing in the computer CPU
- Firmware manipulation in the graphics card
- An auxiliary signal processing board in the data path to the upper monitor
- Manipulation in the monitor controller board

All of these possibilities have been demonstrated. Manipulation at the graphics card is the preferred option to minimize cost and the possibility of adding a delay between the two video paths. Driving a StereoMirror™ monitor is identical to driving a pair of projection displays used to show stereoscopic images with crossed polarizers in the two separate light paths. An off-the-shelf, dual-output graphics card is employed to drive the two monitors, again with no special preparation with the possible exception of the mirror-flip function.

3. OPTICAL AND SYSTEM PERFORMANCE

Because spatial resolution is not sacrificed to achieve stereo separation, as in current autostereo designs, display resolution is not compromised in the StereoMirror™ approach. The full resolution of the AMLCD monitor is displayed. In addition, if the beamsplitter mirror is properly specified and prepared, the chromaticity performance of the original monitor is also largely unchanged. Chromaticity data for a 17-inch diagonal, SXGA (1280x1024) version of the StereoMirror™ is shown in Figure 4. The small color shift from the combination of the two light paths compared to a bare monitor is primarily caused by small differences in the spectral behavior of the mirror in reflection versus transmission.

While less than half the light is utilized from each monitor and combined after the mirror, the resultant luminance and contrast is sufficient for use in a normally illuminated office environment. Luminance of 70 nits is typical for a 17-inch SXGA monitor. Center stereo contrast (defined as full-on white vs full-off black on one AMLCD vs full-off black vs full-off black the other AMLCD) is greater than 150:1 in the SXGA monitor. Stereo contrast can be reduced when the polarizing glasses are rotated from the horizontal, allowing bleed-through between light paths because of the loss of maximum extinction at 90° to the axis of polarization. This can be generated by head tilt. Figure 5 shows modeled data for the effect of head tilt on stereo contrast. A stereo contrast of greater than 50:1 is maintained for head tilt angles of about ±7º. This has proven to provide an acceptable level of head rotation for users tested to date.

Other intrinsic properties of the monitor, such as refresh rate and cell response time, are also not affected in the presentation of stereo in the monitors. The native refresh rate of the monoscopic monitors is used.

Since AMLCDs are typically flicker-free, fatigue or discomfort from flicker is not an issue. This can be an issue with field-sequential shutter glass/CRT stereo systems. While a comprehensive study of user response has not been performed, initial results indicate long term (multi-hour) stereo image viewing with the monitor is possible without discomfort. Cells with liquid crystal response times of 16msec or less are readily available. This switching speed is acceptable for most applications and is unaffected in stereo viewing.

The viewing angle of AMLCDs has been improved greatly in recent years. This viewing angle is preserved in the StereoMirror™ design which allows for simultaneous, multiple-user perception of stereo. The design of the monitor is intended to accommodate a combination of standing and seated viewers. The stereo viewing angle is primarily limited by the viewer's ability to see the lower monitor through the mirror. Unlike most of the current autostereo monitors, there is no restrictive "sweet spot" requiring precise head placement. This adds to the stereo viewing comfort.

As mentioned previously StereoMirror™ monitors are driven using off the shelf graphics cards with no custom software. Stereo-capable software applications designed to operate with OpenGL or DirectX are fully compatible with the StereoMirror design.

The monitor can be readily converted from the stereoscopic/3D mode to 2D by either simply turning off power to one monitor or by lifting the mirror and locking it in place in its hinge track. The unique form factor of the monitor does add a z-axis component that compromises the "flat" profile of monoscopic FPD monitors; however, as shown in Figure 6, the opportunity to place a keyboard and mouse comfortably under the mirror does make for efficient use of desk space.

Another potential compromise is the need for glasses in order to see stereo. Those used in the StereoMirror are simple lightweight, passive polarizing glasses that are inexpensive and have the look and feel of conventional sunglasses. They do not cause flicker discomfort when viewing fluorescent lights or other refreshed computer monitors, as can be the case with the field-sequential goggles. The goggles are also potentially expensive; multiple viewer collaboration using a StereoMirror™ monitor can thus be accomplished much more economically.

One of the most powerful features of the StereoMirror™ concept is that it allows a stereoscopic display to be fabricated in the future from virtually any AMLCD design. To date prototype monitors have been assembled with stereo resolution of 1.3 [8], 2.0, 3.0 and 5.0 MPixels in screen sizes up to 22-inch diagonal. In addition, it is conceivable to have a design that will convert from stereo viewing to a conventional monoscopic, dual-headed monitor through a straightforward mechanical transformation.

4. APPLICATIONS

The stereo image quality obtained from this new technology has the potential to expand the use of stereo viewing in existing markets as well as to open new applications to the benefits of 3D/stereo visualization. Here are some of those potential uses.

One of the challenges of medical imaging today is determining the best method to present volumetric image data to the caregiver in an efficient manner. Much effort is currently being directed at the 3D rendering of these data in a 2D presentation on conventional monoscopic monitors. These images originate from such modalities as magnetic resonance (MR), ultrasound (US), computed tomography (CT), as well as positron emission tomography (PET) and single-photon emission tomography (SPECT). The complexity of these images requires a significant level of sophistication in image processing and great care in the rendering to avoid the incorporation of artifacts when attempting to present a given image using a 3D representation in 2D. Stereoscopic viewing of these images offers the currently unproven possibility of reducing this rendering burden and/or enhancing the performance of the diagnostician through either greater accuracy or throughput, or both. There is also the opportunity to augment the results of Computer Aided Diagnosis (CAD) with a presentation in a stereoscopic/3D mode of images that would include the findings of the CAD analysis. From a display perspective, these opportunities hinge on the ability of a stereoscopic display to provide stereo/3D image quality that is comparable in performance to the premium FPD monitors currently used in diagnostic and clinical practice. The StereoMirrorTM technology is unique in that these same monoscopic medical monitors can be employed with little or no modification to create a stereoscopic/3D display with a high quality image and a high level of user comfort.

Mammography is considered one of the most difficult radiographic exams to interpret. The complexity of these breast x-ray images makes it difficult to discern features of interest among over- or under-lying breast tissue. In particular the in-situ geometry of small particles of calcium, so-called microcalcifications, is important to determine but difficult to confirm, even with two orthogonal views. A stereoscopic/3D analysis of mammographic images holds the promise of improving the early detection of breast cancer by providing depth cues to mammograms. These can potentially provide better insight on superposition and local geometry of lesions and other features of interest. A prior clinical trial [9] made use of stereo viewing of mammograms as an adjunct to diagnosis using film alone. Stereo visualization provided improved diagnostic accuracy in the 129 cases examined. In addition and more importantly, the use of stereo allowed the mammographers reading the images to detect 30% more lesions not visible with film alone. A follow-on clinical trial is currently underway at Emory University[10] that will compare stereo digital mammography to non-stereo digital mammography for improved sensitivity and accuracy of lesion detection and for reduced rate of patient recall. A 5MPixel grayscale version of the StereoMirror™ will be used in this study.

Other potential medical applications for stereoscopic/3D visualization include remote guided surgery, surgical planning. ophthalmic surgical stereomicroscopy and the teaching of anatomy.

Stereoscopic viewing of aerial and satellite photographs has been commonly used for decades in the field of geospatial intelligence. With the advent of digital photography there has been a need to provide high resolution, high quality 3D/stereoscopic monitors for photogrammetry that can also support rapid image panning without image blur. Typical uses include mission planning, satellite reconnaissance and targeting. Long term comfort for professional analysts who use stereo for an extended period is also critically important. With the more recent availability of low cost satellite images for civilian uses such as land use planning, bio-habitat management and even demographic market analysis, there is the possibility of improving the efficiency of this process with stereoscopic/3D viewing.

The Geowall Consortium [11] “makes use of projection systems to visualize the structure and dynamics of the Earth in stereo to aid in the understanding of spatial relationships”. This group believes that the teaching of the spatial relationships required for real understanding of Earth Sciences is best accomplished through use of three dimensional rendering of images on large screen, stereo/3D projection systems. While the StereoMirror™ design is not applicable to large area projection, it is well suited for content preparation and demonstration to small groups. A laboratory of stereo monitors would allow students to directly create and manipulate 3D material.

The knowledge of the atomic-level structure of various biomolecules has grown to such a level of sophistication in recent years[12] that drug discovery/pharmaceutical development for some materials is possible starting from the knowledge of the spatial orientation of individual atoms in enzymes and other targeted proteins. These molecules can have ten thousand or more atoms and therefore a high resolution display is needed. In this process, clearly perceiving the three-dimensional relationship between various parts of a given molecule is critical to the efficiency and accuracy in the early development of a candidate drug. Stereoscopic/3D is also used by crystallographers who determine the structure of these macromolecules. For this application there is a need for a 3D/stereoscopic display that provides high resolution with excellent image quality as well as comfortable stereo viewing in extended use.

Other professional applications well-suited for stereo/3D viewing are oil and gas exploration, Computer Aided Design (CAD) for mechanical and architectural use and visualization of complex computer simulations.

The largest single potential market for stereoscopic/3D displays is in personal computer gaming. The overall game experience and the breathtaking quality and detail found in contemporary game imagery can be enhanced through use of stereo. Stereo/3D increases an important and highly desired feature for gamers – the level of immersion [13]. Dedicated gamers play for extended periods at one sitting and thus fatigue and discomfort with the use of shutter glasses is an issue. Gamers also tend to be very particular about image artifacts, such as those found with shutter glasses and autostereo displays. Our experience to date indicates the StereoMirror™ is well suited for extended game playing. Drivers are available[14] for rendering spatially multiplexed stereo/3D displays such as the StereoMirror™ and allow use of commercially-available games with no custom software.

5-SUMMARY

A novel approach to stereoscopic/3D desktop monitors has been developed that provides excellent image quality, comfortable viewing and simplicity of implementation and use. The StereoMirror™ design uses off-the-shelf-components for its critical parts and employs the full resolution of current AMLCD panels. Stereo images, when viewed with passive polarizing glasses, are flicker-free and thus do not cause discomfort with extended use. The monitor is sufficiently bright to be used in office illumination. The wide viewing angle permits multi-user utilization with no limiting "sweet spot" for stereo, either sitting or standing. It is compatible with existing graphics cards and OpenGL or DirectX applications without custom software and converts readily back and forth between stereo/3D and 2D viewing. The StereoMirror™ approach to stereoscopic/3D viewing has the potential to fulfill the need for an optimum way to visualize complex images and data in the coming years.

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Figure 1 StereoMirror™ Monitor

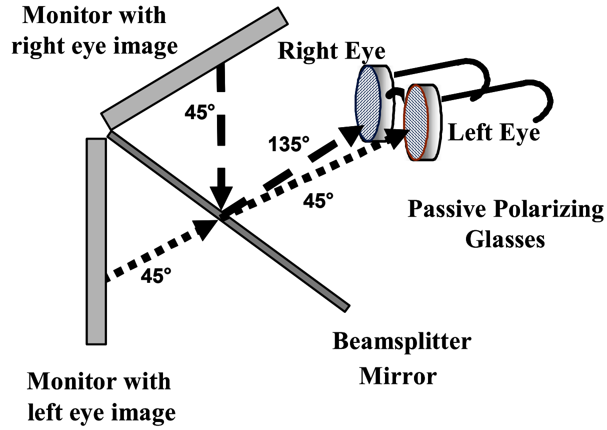

Figure 2 Operating Principle of the StereoMirror™: Conservation of Polarization

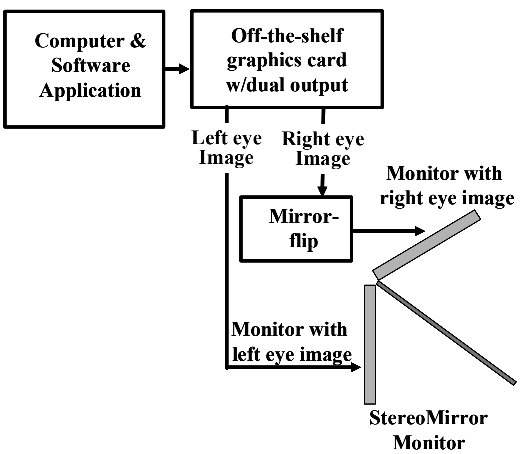

Figure 3 Driving a StereoMirror™ Monitor

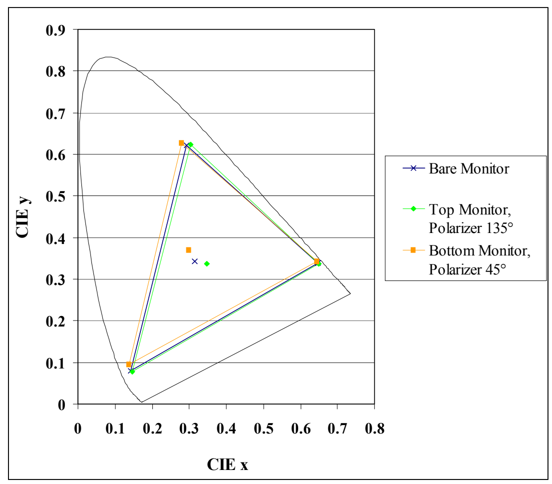

Figure 4 Chromaticity Performance of a 17-inch SXGA StereoMirror™ Monitor

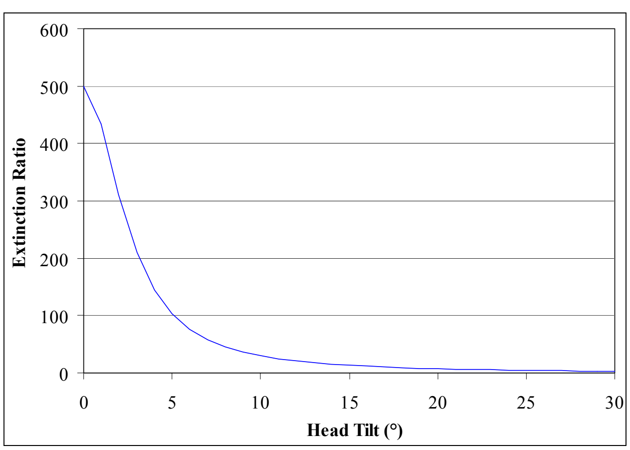

Figure 5 Modeled extinction ratio of a 17-inch SXGA StereoMirror™ Monitor vs head tilt

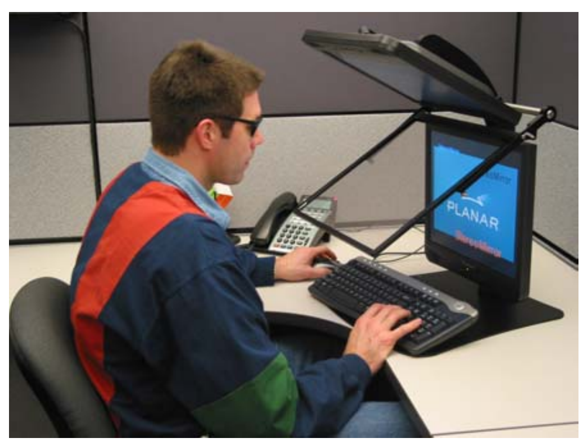

Figure 6 Desktop use of a StereoMirror™ Monitor