Novel View Sequential Display Based on DMD™ Technology

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ABSTRACT

The authors present work that was conducted as a collaboration between Cambridge University and MIT. The work is a continuation of previous research at Cambridge University, where several view-sequential 3D displays were built. The authors discuss a new display which they built and compare performance to previous versions. The new display utilizes a DMD projection engine, whereas previous versions used high frame rate CRTs to generate imagery. The benefits of this technique are discussed, and suggestions for future improvements are made.

Keywords: View-Sequential Displays, 3D Displays, DMDs

1 BACKGROUND

Several view-sequential displays have been demonstrated by Cambridge University which implement a *time-multiplexing* principle and utilize a fast optical modulator, active shutters, and projection optics. Time sequential information is angularly multiplexed by restricting the pupil of a projection system in conjunction with images being displayed on the modulator. In the original systems, custom designed ferroelectric shutters and Cathode Ray Tubes (CRT) were developed. Full color images with as many as 26 views updated at 50Hz [4], and images as great as 50" [1] were demonstrated. View-sequential systems have the advantage of using a single modulator, which is much more economically feasible than other multi-view systems. They also provide viewing zones which naturally abut one another, which is a subject of difficulty for other multi-view displays [2]. However, they require large projection optics, which limits the field of view. They also throw away a lot of light because of the active shutter, which increases as more views are included in the system.

The authors became interested in building a new view-sequential display in the Summer of 2002. We decided to build a system identical to the earlier view-sequential displays built by Cambridge University, except using a DMD projection engine to generate pixel information instead of CRTs. The system was presumed to offer the potential for increased brightness, greater pixel bandwidth, and decreased display size.

2 SYSTEM DESIGN

Vizta3D (now LightSpace Technologies) generously gave us an entire 800x600 pixel DMD projection system, complete with drivers, a PCI data transfer card, and proprietary software to drive the display. The projection engine consists of:

- RGB separator and combiner optics.
- 3 800x600 pixel DMDs, one for each color.
- Projection optics.

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- Driver electronics which display 5-bit RGB images at 800fps on each DMD.
- Framebuffer to store images with high speed connection to the driver board.
- PCI data transfer card to load bitmaps from a computer to the display.
- 80 volt, 5 amp power supply for the DMDs and projection lamp.
- 3' x 3 x3' storage and transportation container for the projection engine.

We also received a custom designed FLCD shutter and driver from Cambridge University. The shutter is 100x100mm and consists of sixteen columns which are individually addressable. The device is specially designed for use in view-sequential displays, where each column limits the viewing angle of a single view. Each column can be refreshed as quickly as 1-2Khz. As it is used in this display, each column of the FLCD is switched open for 1/800sec and then waits 1/50sec to switch open again.

2.1. Optical Design

The optical design of the proposed system is perhaps the simplest aspect of the display. There are only five components: DMD, diffuser, FLCD shutter, projection lens, field lens. The optical design that we implemented is identical to the design of the 10" and 25" cambrige view-sequential displays. This design was chosen for simplicity. The use of a convex mirror to replace the output lens was considered, but the expense of this item prevented us from including it in the first generation system.

View-sequential display optics are a type of image relay system. In the simplest case, the object is replaced with an SLM, and a shutter is placed in front of the projection lens to further restrict both the *entrance* and *exit pupils*.

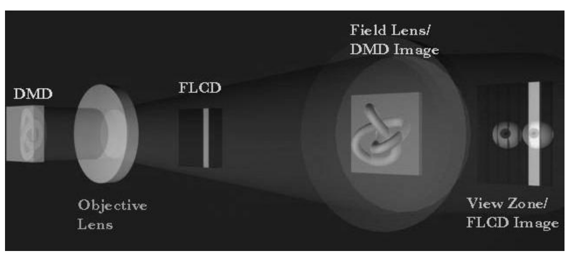

Figure 1. *view-sequential displays are a variant on the GIRS system, whereby the entrance pupil is limited by an active shutter.*

This design allows the viewing of the SLM image to be restricted to a limited portion of the viewzone. As soon as the SLM generates a new image, the portion of the viewzone that is viewable is shifted, and this is repeated until the entire viewzone is filled. The shutter and the SLM must be precisely synchronized in order to ensure that each view is correctly displayed, and an entire set of views must be refreshed within 1/50sec.

The final system utilized the long path lengths that are inherent in the display to raise the viewing screen of the display to standard viewing height. The optics are shown in Figure 2, and the design is very similar to the standard view-sequential optics, with a few folding mirrors included to optimize image, lens separation, and viewing distances. A diffuser is included to eliminate the visibility of the projector bulb filament since viewers are essentially looking down the optics of the system. A variety of diffusers was chosen, and one was eventually used which diffuses at an angle of about 20^o. Less powerful diffusers did not eliminate the filament image and caused the viewzone to be unevenly illuminated.The relevant quantities are:

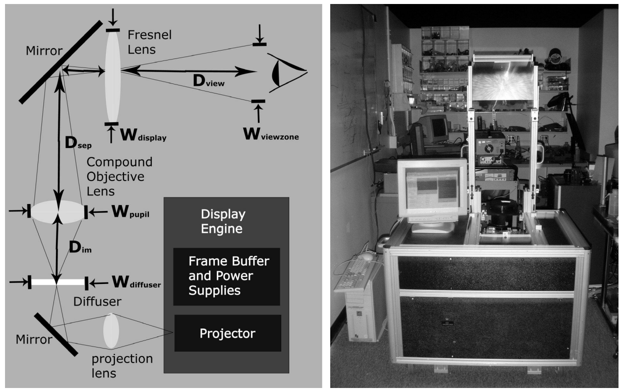

Figure 2. *The left image shows a side view of the final optical design for the view-sequential display, listing all the components and the relevant distances. The right picture shows the front of the display. A Fresnel lens is hoisted above the projection engine, and sits at about 5' above the ground.*

- $W_{diffuser} = 5cm$
- $W_{viewzone} = 30cm$
- $W_{display} = 30cm$
- $W_{pupil} = 20cm$
- $D_{diffuser} = 10cm$
- $D_{sep} = 40cm$
- $D_{view} = 125cm$
- $F_{eff,objective} = 75cm$
- $F_{eff,field} = 75cm$

The magnification of the diffuser image is 6 and the distances are given relative to the principal planes of the lens that is creating the image.

2.2. Hardware Implementation

The hardware implementation for the Cambridge/MIT display is an original design that was developed by Cambridge university, Vizta3D, Christian Moller, and the author. All of the projector electronics was developed by Vizta3D, and the FLCD dirver electronics was developed by John Moore at Cambridge University.

Four electronics components were required to drive the display: DMD driver, FLCD driver. FPGA synchronization device, and desktop CPU for image generation and data transfer. The DMD and FLCD driver were provided for us. The DMD driver provides a sync output signal that provides a rising edge every time a new image is loaded on the DMDs. This signal was used to activate the successive LCD panels in Vizta3D's DepthCube^{TM} display. The FLCD driver was designed to receive two input signals: a horizontal sync and a Z-sync. The horizontal sync is used to sequence to successive shutter columns, and the Z-sync is used to reset the sequence back to the first column. An FPGA was built to generate the Z-sync signal from the signal generated by the projection engine. The FPGA feeds both the h-sync and Z-sync signals to the FLCD driver. The FLCD driver requires a 5volt input to control logic as well as +/-40volts to switch the cells between states.

Figure 3. An image captured by a camera whose pupil was placed within a single slit.

A NIDAQ PCI card was used to transfer data to the frame buffers that feeds the DMDs. The card outputs data on a 32bit wide bus, which runs at 20MHz. Data transfer is designed so that a single pixel is sent at a time over the bus, and half of the lines are consequently wasted. The result is that an entire set of views can be updated in 16 views x 800x600pixel / 20Mpixels/sec = .38sec. In practice, loading times closer to .5sec were demonstrated. There are two frame buffers so that a new set of images can be loaded while still displaying the previous set. The framebuffer was designed to receive an entire set of images at once, and was not capable of loading partial frames. Both of these factors severely limited the maximum achievable interactivity of the display.

2.3. Imaging

The imaging pipeline was developed in two stages, and computer generated imagery was used exclusively. The first technique was to use 3D modeling software to generate a sequence of bitmaps that could be loaded onto the display all at once. This was a very tedious process, and involved transferring data from one machine to another. Achieving desired images was an iterative process, and very time consuming. The second technique was to utilize a custom built software application which provided the following:

- Load and manipulate 3D files (e.g. .obj, .3DS, etc.).
- Provide custom rendering based on chosen viewing position.
- Reformat images to load into the frame buffer correctly.
- Call the NIDAQ API to transfer data to the frame buffer.

Though it required building new software, the second technique dramatically reduced the iterations between loading images onto the display. The new software also set a framework to achieve the maximum interactivity that the display is capable of. It was the hope of the author to be able to load a set of images close to 1sec, thus providing reasonable interaction with 3D content. All the rendering was done on a P3 desktop without a fast graphics card, and generating and formatting the data typically took 5-10sec. Camera views were generated by translating and shearing a virtual camera along a track which represents the viewing zone. The ratio of viewing width to distance for the display was set to equal the virtual camera distance to track width ratio.

3 RESULTS

The display produces very satisfactory 3D images, with exceptional 2D image quality. The color depth of the images is remarkable, and the images are quite bright. The display has a brightness of $40cd/m^2$ and a contrast of about 60:1. Figure 4 demonstrates the details and colors that the display is capable of. Images as deep as 350cm have been demonstrated.

3.1. Discussion on Size Constraints of the System

The size of the projection lens is of critical importance to the system, for it determines the maximum viewing angle that can be achieved. The lens must have a large Numerical Aperture (NA) if it is to be placed close enough to the field lens as to provide a reasonable viewing angle. Generally, such a lens will be expensive, and will probably consist of a compound of several lenses, thus increasing the size of the system. Typically the magnification of the objective lens must be greater than 4 because SLMs are currently built so small. In order for the image to be magnified, it must be placed greater than twice the focal length from the objective lens.

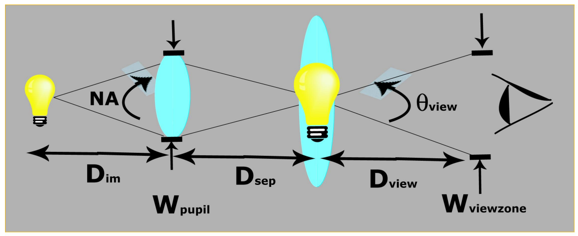

Figure 4. *There is a fundamental limit set on the viewing angle θ_{view} that is set by the numerical aperture of the objective lens. The focal length of the objective lens is designated f_1, and the focal length of the field lens is designated f_2.*

There are two constraints which limit the viewing angle of this type of system:

- The Numerical Aperture of the objective lens typically must be greater than one.
- The objective lens must magnify the image of the SLM.

By the paraxial approximation the magnification for the field lens is:

$$M_2 = \frac{W_{viewzone}}{W_{pupil}} = \frac{D_{view}}{D_{sep}} \tag{1}$$

The angle of the cone of rays converging from the objective lens which focus the SLM image sets the viewing angle of the display. In the paraxial regime, this means that the ratio $\frac{W_{pupil}}{D_{sep}}$ defines the viewing angle. The magnification for the objective lens is:

$$M_1 = \frac{D_{sep}}{D_{im}} = \frac{NA_1 \times W_{pupil}}{D_{sep}} \tag{2}$$

Where $NA_1 = \frac{D_{im}}{W_{pupil}}$. Rearranging gives:

$$\frac{W_{pupil}}{D_{sep}} = \frac{NA_1}{M_1} \tag{3}$$

This together with the inequalities $M_1 \geq 4$ and $NA_1 \geq 1$ and the relation $\theta_{view} = 2 \times \frac{W_{pupil}}{2 \times D_{sep}}$ gives the result:

$$\theta view \lessapprox 15^o \tag{4}$$

The results of this analysis demonstrate that it is hopeless to use unmagnified microdisplays with this technique because magnifying the SLM image places such a large restriction on the viewing angle of the display. Indeed our display only had a viewing angle of $\theta_{view} = 13.8^o$. The initial systems built by Cambridge University did not need magnification because the CRTs used were very large, and thus wider viewzones could be achieved. In any case, if a viewzone is too large, it will violate the paraxial regime and cause distortions to viewing positions that are too far off-axis. Other techniques for projection-based multi-view displays such as Travis describes in[?] will have to be developed if these displays are to achieve success.

4 SUGGESTIONS FOR FURTHER WORK

The results of this paper are remarkably impressive, but several improvements on image quality could be made. The color depth of the display should remain the same, for the richness in colors greatly attributes to a pleasurable viewing experience. The resolution of the display screen should be sacrificed to achieve greater sampling of parallax information, but this is not possible with the current projection engine. The next generation DMD projection system is capable of displaying images at twice the speed of the engine used for the current system, which could allow twice as many views to be displayed. The newer DMDs also allow partial frames to be updated at increased frame rates. This would allow even more views to be included in exchange for lower resolution images sent to the display screen. A display with $1/16^{th}$ the maximum resolution would still provide 256 samples on the display screen, and allow an equivalent amount of parallax sampling to be achieved. Such a display would be capable of conveying as much depth as current commercially available volumetric displays, but with the added feature of occlusion.

Initially, it was considered that one of the advantage of using DMDs over CRTs was to ensure that the minimum resolution of the eye be met. Our view-sequential display had a pixel size of .375mm, which matches the minimum resolution of the eye at a viewing distance of 430mm. Viewers are ensured to have this condition met, and discontinuities in the observed image are avoided. Observations made on the display reported in this paper indicate that this approach may be unnecessarily stringent. It might be a greater advantage to have fewer and larger pixels, and use the extra bandwidth for more parallax sampling so that deeper images can be displayed.

An improved version of the system could utilize a larger diffuser image, reducing the magnification needed by the objective lens. Such a system could have a much larger viewing angle, but would *increase* the size to greater than previous versions. The success of this display is in demonstrating a greater bandwidth system with much greater brightness.

5 FINAL REMARKS

The display that was built did revive an interest in view-sequential 3D and demonstrated that the progress of fast switching binary devices has opened up new possibilities for this technique. The time-multiplexing principle was at the heart of the success of this display, as with the Perspecta ^{TM} , and DepthCube^{TM} displays that Actuality and LightSpace currently sell. The *time* and *spatial-multiplexing* techniques compete for commercial viability, and until recently, *spatial-multiplexing* had predominantly found itself in the lead. The success of the Cambridge/MIT view-sequential 3D display marks the strength of the *time-multiplexing* technique.

ACKNOWLEGDEMENTS

This work would not have been possible without the generous donation from Alan Sullivan et. all, previously of Vizta3D.

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