58.3: A Solid-state Multi-planar Volumetric Display

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Abstract

The DepthCube™ 3D display is a solid-state multi-planar volumetric display system in which a DLP based high speed projector projects slices of the 3D scene onto a stack of LC scattering shutters acting as an electronically controlled projection volume. The scattering shutters are based on Polymer Stabilized Cholesteric Texture material. Highly continuous appearing 3D images are obtained through multi-planar anti-aliasing.

1. Introduction

A high performance three dimensional display system has been the goal of many experimental and entrepreneurial quests over at least the last 40 years [1]. And the level of effort has only increased recently due to the exponential increase in the computational performance of modern computers and the wide range of 3D applications that run on them. In fact, by some accounts over $55 Billion [2] will be spent in 2003 alone on 3D computer hardware, software, systems and services, all in the relative absence of a high performance 3D display system.

2. DepthCube™ 3D Display System

In order to address the enormous demand for three dimensional displays, we have developed and are commercializing a system called the DepthCube™ 3D Display System. A schematic diagram of a DepthCube™ 3D Display System is shown in figure 1. The DepthCube™ Display System is a solid state, rear projection, volumetric display that consists of two main components: a high-speed video projector, and a multi-planar optical element (MOE) composed of a air-spaced stack of liquid crystal scattering shutters. The high-speed video projector projects a sequence of slices of the 3D image into the multi-planar optical element where each slice is halted at the proper depth. Proprietary multi-planar anti-aliasing algorithms smooth the appearance of the resultant stack of image slices to produce a continuous appearing truly three dimensional image.

Figure 2 shows a block diagram of the architecture of the DepthCube electronics. The system is divided into four circuit boards: a main image generator (IG) board and three DMD boards, one each for red, green and blue, that are mounted onto the color separation/recombination prism of the DLP video projector. The IG board receives image data from a computer via a high speed PCI digital output card at a rate of 20 Mpixels/sec. A front-end input decoder section converts the data signals into a custom internal format and routes them to the three IG board color channels. The front-end section also has a daughter board connector so that additional transfer protocols, such as Gigabit Ethernet or FibreChannel, may be implemented in the near future without an IG board redesign.

Figure 3 shows a block diagram of a single DepthCube color channel. It consists physically of an IG board color channel (an FPGA, a pair of 16 MByte DDR SDRAM memory chips configured as a dual ported, double-buffered multiplanar frame buffer, and a pair of SRAM memory chips used as an output buffer) and a set of DMD board components (a DLP Discovery controller, a DLP reset ASIC and an XGA DMD). Signals are transferred from IG board color channels to the DMD boards through a coaxial ribbon cable.

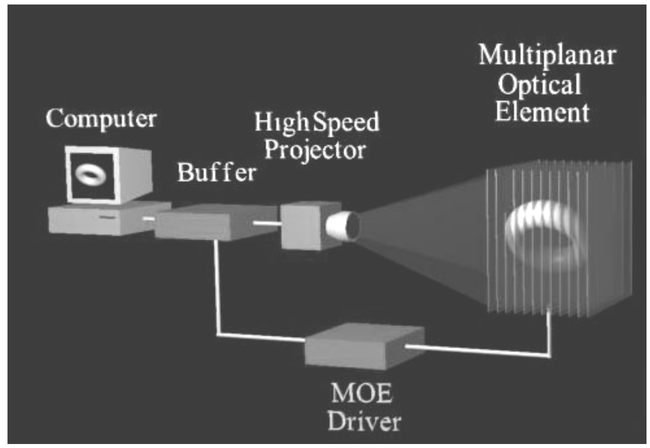

Figure 1 Schematic diagram of the DepthCube™ 3D Display System.

Each color channel receives 5 bits of brightness data, 10 bits of depth data encoding a 5-bit integer portion (z_i) and a 5-bit fractional portion (z_f), and 10 bits each of x and y position data. Depending on the data transfer mode, the depth data can be supplied on a per-pixel basis from the computer (plane transfer mode) and used for anti-aliasing, or obtained from the front-end decoder based on transfer count in the same way as the x and y data are generated (block transfer mode).

While a new image is being written into one of the two frame buffer banks, the previous image in the other buffer bank is being displayed. The DRAM memory manager transfers a single plane of image data to the bit plane formatter where the 5-bit per pixel image is converted into five 1-bit per pixel bit plane images. The bit plane images are temporarily stored in the output buffer before being transferred to the DMD via the DLP Discovery controller. Control signals from the color channel determine the sequencing of bit planes and hence the bit depth and frame rate.

In plane transfer mode, the anti-aliasing processor uses the brightness data (B) and the fractional part of the depth (z_f) to compute two new brightness values, B_{Near} and B_{Far}, equal to

$$B_{Near} = B \cdot \left(1 - \frac{z_f}{32}\right)$$

$$B_{Far} = B \cdot \left(\frac{z_f}{32}\right)$$

that are written to the same pixel on two consecutive planes. The address processor uses the x, y, and z_i data to compute the addresses of the two pixels by

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$$\mathrm{Addr}_{Near} = x + 1024 \cdot y + 1024 \cdot 748 \cdot z_i$$

$$\mathrm{Addr}_{Far} = x + 1024 \cdot y + 1024 \cdot 748 \cdot (z_i + 1)$$

The memory manager performs two 8-bit write operations for each pixel transferred in plane transfer mode, storing the B_{Near} value in the Addr_{Near} address and the B_{Far} data in the Addr_{Far} address

In block transfer mode, the brightness value transferred from the computer is written without modification into the frame buffer at the address given by the transfer count. The data consists of 20 images, each 1024 x 748 pixels, corresponding to the 20 planes of the display. Anti-aliasing, if any, must be performed by the computer.

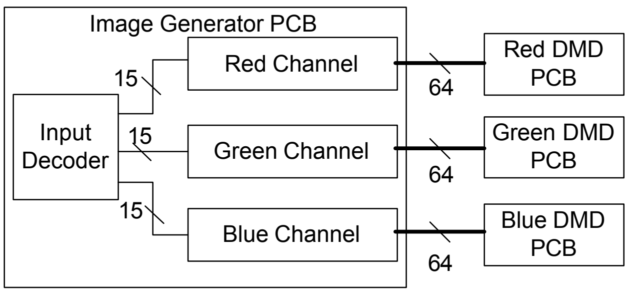

Figure 2. Block diagram of DepthCube Electronics.

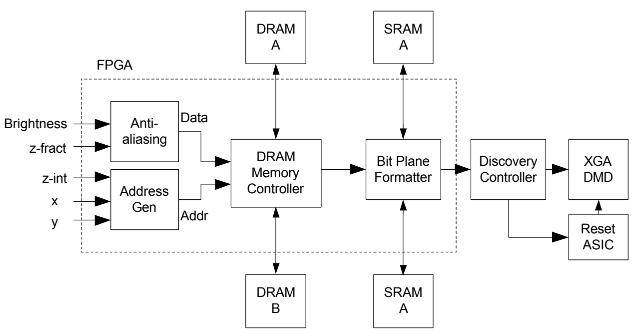

Figure 3. Block diagram of a DepthCube color channel.

3. LC Scattering Shutters

The multiplanar optical element (MOE) is a stack of 20 air-spaced liquid crystal scattering shutters. The MOE acts as an electronically variable solid-state projection volume and, in conjunction with the high speed video projector, creates the 3D image. The shutters are based on polymer stabilized cholesteric texture (PSCT) material developed at Kent State University [3]. Figure 4 shows the transmission as a function of time of one of the scattering shutters. The shutter exhibits 88% transmission in the clear state, 2% transmission in the scattering state (10° collection angle), and switches from clear to scattering in 0.39 msec and from scattering to clear in 0.08 msec. The application of an appropriate anti-reflection coating can increase the clear state transmission to over 96% giving an overall MOE transmission of 44%.

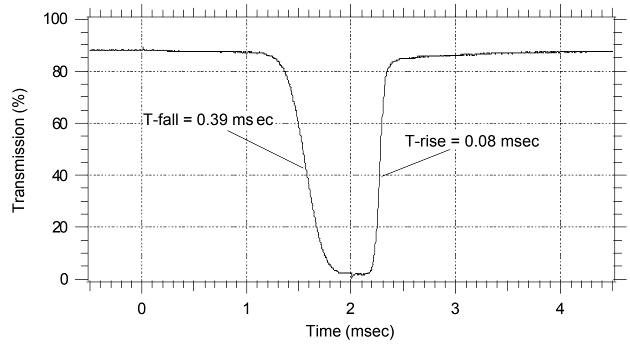

Figure 4. Transmission vs. time of PSCT shutter.

4. Multiplanar Anti-aliasing

If image slices are transferred to the DepthCube's framebuffer without special processing the resultant image will look like a stack of 2D slices rather a single continuous 3D image. To eliminate the appearance of depth discontinuities we have developed the technique of *multiplanar anti-aliasing*. Anti-aliasing is achieved by using the fractional portion of the z value transferred to the framebuffer to compute the proportion of the given RGB brightness to assign to the adjacent planes of the display. For example, if a given pixel is transferred to the DepthCube with a z value of 5.25, 75% of the given RGB brightness will be written to the memory location associated with that pixel in plane 5 and 25% will be written to the same pixel in plane 6. This process is similar to conventional anti-aliasing used to smooth the "jaggies" in lines in 2D images.

The effectiveness of the multiplanar anti-aliasing in reducing the level of perceived discontinuity of the resultant 3D image is difficult to overstate. For images having large continuous shapes the image looks completely smooth out to large off-axis viewing angles (~45°). For fine lines like those associated with wire frame images multiplanar anti-aliasing is very effective to an on-axis viewer and degrades gradually as viewing angle increases. Multiplanar anti-aliasing effectively leverages the subtle character of visual perception to synthesize perceived depth planes between the physical planes of the display. Using a 5-bit fractional portion for z gives a 32-fold increase in the perceived number of planes with the result that the commercial DepthCube system has 465.7 Million perceived voxels.

5. DepthCube System Performance

As mentioned above, the DepthCube supports two main data transfer modes, plane transfer mode and block mode. The strength of plane transfer mode is that the DepthCube can be updated at nearly real-time rates because the z-buffer data is readily available from the frame buffer of conventional 3D graphics boards, and because only a single plane of data consisting of 1024 x 748 RGBZ values must be transferred to create a 3D image. However, the resultant image has only a single 3D surface at any depth within the display. Using block transfer mode, the value for every voxel in the display is transferred to the frame buffer. This method is obviously slower, but allows multi-surface images or true volumetric images, such as those associated with MRI or geophysical data, to be displayed.

Additional flexibility is provided by using sub-plane and sub-block transfer modes, in which only a portion of the frame buffer is updated, as well as through the use of transfer flags. The flags permit multiple data transfers in any mode to be combined together before the image is shown. Also older images may be retained in the frame buffer in circumstances where significant portions of the image are consistent over many updates, e.g. terrain data in military command and control applications. This flexibility in image generation enables 3D images of great complexity to be created very simply.

The performance specifications of the current DepthCube commercial system are shown in table 1.

Resolution	1024 x 748 x 20
Physical Voxel count	15.3 Million
Perceived Voxel count	465.7 Million
Color depth	15-bit
Refresh rate	60 Hz
Update rate	20 Hz
Image volume	15.6” x 11.8” x 4.1”

Table 1. Performance specifications of the commercial DepthCube 3D Display Systems.

By its very nature the 3D images in the DepthCube™ Display System have all of the depth cues found in viewing real objects thereby giving rise to the phrase “true 3D display”. Unlike stereoscopic and autostereoscopic displays, the DepthCube™ maintains the normal relationship between eye focusing and convergence to produce a very comfortable and natural 3D viewing experience. The DepthCube™ Display System also provides both horizontal and vertical parallax. The 3D images can be viewed from any distance over a wide field of view (~90°) by a large number of viewers, each with the appropriate perspective. Unlike other volumetric displays the DepthCube™ has no rapidly spinning parts, and the rectilinear Cartesian geometry of the DepthCube™ allows the entire display volume to be used without image distortion or obstruction. The 15-bit color capability of the DepthCube also enables the display of shaded and texture mapped 3D images. Finally, the DepthCube™ 3D Display System’s Cartesian geometry matches the geometry used in computer graphics hardware thereby enabling rapid rendering of the 3D imagery with realtime interactivity from standard graphics hardware.

Images in the DepthCube™ Display System can be either solid textured surfaces, translucent textured surface with background surfaces visible at the appropriate depth, wireframe images, or complete volumetric datasets in which a significant number of display voxels are activated. In all cases the images are truly three-dimensional and provide an automatic and intuitive understanding of the data.

Figure 5. Photograph of a commercial DepthCube 3D Display.

5. Conclusion

The development of the DepthCube™ Display System represents a significant breakthrough in three-dimensional visualization as well as an important advance in display technology. The DepthCube™ Display System technology is capable of producing high resolution, three-dimensional images from existing software that provide natural eye focusing and convergence, as well as both horizontal and vertical parallax. The 3D images are full color, have a large number of simultaneously addressable voxels, and are visible over a wide field of view.

6. Acknowledgements

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7. References

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