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A Single Chip DLP Projector for Stereoscopic Images of High Color Quality and Resolution

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Abstract

We present a novel stereoscopic projection system. It combines all the advantages of modern single-chip DLP technology – attractive price, great brightness, high contrast, superior resolution and color quality – with those of active stereoscopy: invariance to the orientation of the user and an image separation of nearly 100%. With a refresh rate of 60 Hz per eye (120 Hz in total) our system is flicker-free even for sensitive users. The system permits external projector synchronisation which allows to build up affordable stereoscopic multi-projector systems, e.g., for immersive visualisation.

Categories and Subject Descriptors (according to ACM CCS): B.4.2 [Input/Output Devices]: Image display
I.3.1 [Computer Graphics]: Three-dimensional displays

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1. Introduction and State of the Art

There are numerous approaches to realize stereoscopic projection systems, each with its strengths and weaknesses. In the following we give a short overview of the various techniques. This is then contrasted by user wish list, according to which our new stereoscopic projection system, which is the key contribution of this paper, performs very well.

Stereoscopic imaging systems can be roughly classified by the way the images are encoded: time encoded (frame interleaved) systems with shutter glasses, wavelength encoded systems using anaglyph style glasses, wavelength multiplex systems, and systems exploiting the light wave orientation using polarisation [Dom81].

1.1. Time encoded systems

In time encoded systems the images for the right and left eye are displayed one after another. Typically the viewer wears a shutter glasses that separate the images of the two eyes. At any given moment, only one eye can see an image, the other sees black. When used with a CRT monitor, both scan line and full page modes are available. In scan line mode the image (and eye shutter) is swapped every scan line, in page mode the images are swapped every full frame. CRT monitors, however, are losing market shares, and this mode requires very fast shutters. Figure 1 shows the typical, very short synchronisation impulses, the control line for shutter emitters, and the resulting states of the shutter glasses. If the frequency of the alternating images in page flip mode is high enough, normally above 120 Hz, the observer does not recognize any flicker. Time encoded images may also be generated by projection systems with one or two projectors, for instancde using a CRT projector instead of a CRT monitor.

In [Wer02] Texas Instruments describes a 3-chip DLP system with an associated quad buffer, i.e., with a front and a back buffer for each eye, very similar to the quad-buffers of an stereo capable OpenGL graphics board. This system is used in the well known stereo projectors from Christie Digital and Barco.

Systems with two sources need a very accurate blanking mechanism, such as the one from Ling [Lin89] using various rotating shutters. Another alternative are external LC (liquid crystal) shutters, furthermore [Wer02] uses the blanking of DMD columns to remove the unwanted part of the image. – We have also built a two projector setup for DLP systems, one that uses the projector's own digital micro mirror device (DMD) as a shutter [Hop03], which will be described in section 3.1 later in this paper.

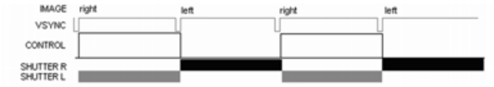

Figure 1: *Time encoded systems: Typical synchronization signal for infrared shutter glasses.*

1.2. Wavelength encoded systems

Simple wavelength encoded systems use two different colors, which is known as *anaglyph* encoding. Since full colors are used, e.g., red/blue or red/green, the perceived 3D image is only greyscale. Frequency multiplexing - known as *Infitec* - overcomes this problem by using three pairs of frequency ranges for red, green, and blue light, i.e., one small range of red for the right and another for the left eye, etc. The ranges of a pair are as close as possible, and each of the images has its own range of red, green and blue light, not overlapping with the others color range. Disadvantages are a perceivable color shifts between both images, and a loss of brightness since the filters let only pass very narrow wavelength ranges.

1.3. Wavelength orientation encoding

Polarizing filters are probably the most popular way to separate the right and left images. In a two-projector setup, two pairs of static linear/vertical filters are used, one pair with the projectors, one in the glasses. With linear polarization, light is polarized at 45 and 135 degrees, so tilting the head by 90 degrees exchanges right and left. Circular polarized light results from adding a lambda/4 retarder to the linear filter, thereby adding a rotational component to the light beam. With circular filters the rotation of the observer along the light beam is less critical, and results only in color shifts.

Single-projector stereo is possible with a Z-Screen [NuV01] in front of a fast projector to change the polarization with a liquid crystal rotator. The alternating images can now be visualized by *passive glasses* (with static filters) instead of *active* ones that have LC shutters.

1.4. Projection Systems

The different ways of separating the right/left images require certain capabilites from the display devices. There are essentially four different types of projection systems, CRT and LCD, LCOS and DLP. CRT and LCD are well known.

LCOS projectors. Based on HTPS (High Temperature Poly Silicon), LCOS is imilar to LCD as it consists of a liquid crystal layer on top of a pixelated, highly reflective substrate. Another layer below the substrate holds the pixel control electronics (Figure 2a). LCOS panels are currently manufactured in 1280×768 (720p) and 1920×1080 (1080p). Very soon, LCOS single chip *Rear Projection TV* (RPTV) sets with a color wheel will be commercially available.

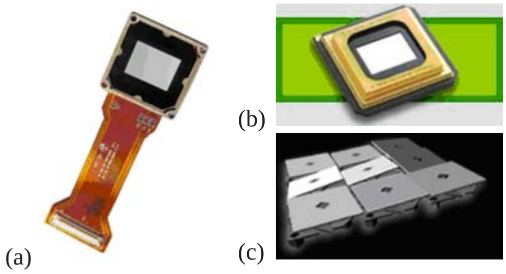

Figure 2: *(a) LCOS Panel (image by MicroDisplay), (b) 0.9" DMD chip (image by TI), (c) DMD micro mirrors (also TI)*

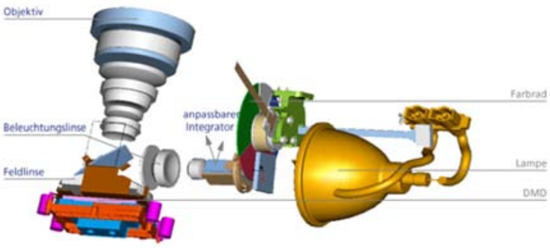

Figure 3: *Typical DLP projector (image by ZEISS). An elliptic mirror sends the light through the color wheel into an adaptable integrator rod. A condensing lens gathers it, and two reflective prisms lead the light onto the DMD, which reflects it either through the lens, or back into the lamp.*

DLP projectors. The famous *Digital Light Processing* (DLP) technology from Texas Instruments is based on the *Digital Micro mirror Device* (DMD) (Figure 2b). It was described by Hornbeck in 1991 [Hor91]. The DMD chip is a *micro electro mechanical system* (MEMS) consisting of an array of bistable mirrors fabricated over a CMOS memory substrate. Projection systems based on this technology vary in configuration, including 1-chip, 2-chip and 3-chip designs.

Single-chip DLP systems contain one DMD and a color wheel (see Figure 3); a typical design is described in [Shi04]. The light shines through the color wheel onto the DMD, which reflects it either through the lens system onto the screen, or back into the light source. The DMD consists of thousands of tiny mirrors (Figure 2c), so the chip itself can not modulate the color. It needs a color wheel with at least three primary colors, i.e., red, green, and blue, and usually white (transparent). Since a mirror is either completely on or off, the intensity of the light and, thus, the color, must be controlled by a sophisticated pulse-width modulation scheme; it is more fully described in [DH98].

Source	Linear Polariz.	Circular Polariz.	Infitec	Observer Shutter	Source Rotator	Source Shutter
Single projector stereo setup solutions						
CRT				●	●	
LCD						
DLP	●	●	●	●	●	
LCOS						
Double projector stereo setup solutions						
CRT	●	●	●	●		●
LCD	●	●	●	●		●
DLP	●	●	●	●		●
LCOS	●	●	●	●		●

Table 1: *Encodings combined with projector types*

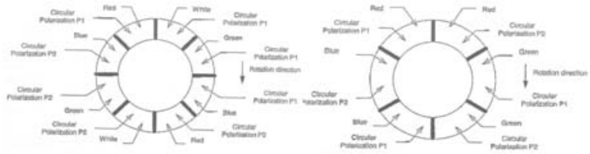

Figure 4: *Polarized color wheels from [DS02]*

1.5. Combinations for Stereoscopic Viewing

Table 1 summarizes the valid combinations of single and double projector stereo setups.

One interesting idea described by Divelbiss in [DS02] is to build circular polarization into the color wheels. Monoscopic color wheels have three (RGB) or four (RGBW) segments, so two such sets of colors are needed for stereoscopy, one in either of the two polarization orientations.

Frequency multiplex can be used with any projector that produces the respective wavelength, although an advanced color correction may be required for high quality colors. Combining circular polarization with LCD is difficult since the polarisation of red and blue light is usually orthogonal to green light. The green light must be rotated with special filter sets that add circular polarization, or special projectors must be used that avoid splitting the light into orthogonal beams.

A shutter for single projector stereo can only be used with fast projectors (CRT, DLP, LCOS), but we do not know of any LCOS systems fast enough to swap images every 8 or 10ms. – Note that with double projector stereo, almost any encoding can be used with any projector type.

1.6. User whish list

Good products require good technology, but user-centric design requires also to take the views of customers into account. In the following the diverse, and sometimes contradictory, requirements are summarized that we have collected over time:

- **Easy mechanical setup**
  A double projector setup has be adjusted with respect to the distance to the screen. This is tedious and difficult, and it requires high quality shift lenses and racks.
- **Avoid non-standard materials**
  Mirrors and projection screens that maintain the polarization are very expensive. Maintaining polarisation and maximum diffusion are conflicting goals, silver screens for instance present a "hot spot".
- **Comfortable glasses**
  Bulky glasses are not accepted by a wide public, light weight is mandatory.
- **Avoid using jkfilters if possible**
  Brighter projectors are usually much more expensive. So using filters should be avoided whenever possible, not to take away any brightness from the image.
- **Even color degradation**
  The colors of both channels should be equal throughout whole the lifetime of the lamp(s).
- **Color quality**
  The colors on the screen should be at least as good as those of normal mono projectors.
- **High resolution and brightness**
  Users always want the highest possible resolution, at least SXGA 1280×1024 Pixel. Only a standard brightness of at least 2000 ANSI lumen permits to enjoy 3D in rooms that are not much darkened.
- **Cost**
  If possible a stereo projection system should not be more expensive than a monoscopic one.
- **Practical usability**
  Only small, light weight, transportable systems permit to bring 3D to a customer's site. The setup procedure must take minutes, not hours, and it must be robust and easy.
- **Input bandwidth**
  Many graphics boards today are dual-headed, i.e., they can feed two monitors. A stereo projection system with dual-headed input is greatly preferable, since with 2×60 Hz it avoids any input bottlenecks. And it allows scalabilty: For the utmost 3D performance, the input channels may be fed by a pair of two (loosely) synchronized PCs.

Quite surprisingly, this wish list almost rules out the most popular solution for stereo projection, a pair of stacked projectors with polarizing filters and a silver screen. Its alternative, Infitec, takes away too much light, and it introduces color problems.

This leaves **active stereo** as the only viable option. Taking the color degradation into account only a single projector is preferable. It should not use any additional filters, and it should permit dual-headed input for maximal bandwith. One remaining issue is to develop lighter glasses in order to avoid the bulky "Crystal Eyes" style units.

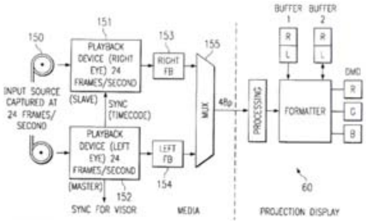

Figure 5: *3-chip stereo DLP from [Wer02]*

2. Stereo DLP Systems – Current State of the Art

A DLP system consists of the *interface* and the *projection display* [Hor97, SOA91]. The interface receives the source input, scales it, converts it to scan frequency (scan conversion), and stores it in the high speed RAM of the the projection display containing the formatter and the DMD.

The 3-chip design from Werner [Wer02] uses two sources that are multiplexed and scan rate converted. The alternating images are fed into the formatter with a quad instead of a double buffer (Figure 5), and alternatingly transported to the three DMDs with approx. 100Hz. In reality, however, three formatters are needed, with their RAMs working in parallel. It is clear that input frame rates can not be as high as the output to the DMD since the quad buffer may be read out multiple times before a new image pair has made its way through the formatter.

The 1-chip DLP system from Develbiss [DS02] encodes two images in a vertically striped image, which halfes the horizontal resolution. A complex processing unit uses column blanking / column doubling to convert the input image into the native DMD resolution, to avoid any scaling by the formatter. Another commercially available solution is the Infocus DepthQ projector that displays frame interleaved SXGA (800×600) stereo images with 120 Hz. It uses chipsets for higher resolutions, thus higher bandwith, for displaying more images of lower resolution.

2.1. Discussion

The 3-chip design from Werner is quite expensive and accepts only interleaved input (no cluster rendering), while the one from Develbiss needs complex processing and reduces resolution; also the image processing in the formatters may add significant errors to the column interleaved images. The DepthQ projector also allows only low resolutions.

A fundamental problem of single-headed input is the limited bandwidth of the formatter and the associated memory, which does not allow a throughput of maximum resolution images at 120 Hz. For higher stereo resolutions the speed of the memory (already fast RAMBUS) had to be doubled, as well as the processing power of the formatter ASIC. So a double bandwidth will never be available with cheap mass market components.

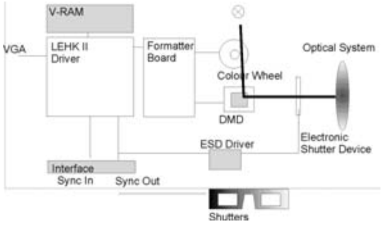

Figure 6: *Standard single DMD projector with associated shutter and synchronisation*

Figure 7: *(a) The Projectiondesign F1+ used for active stereo, (b) a color range test image*

3. Next Generation 3D Projection Systems

Using two projectors: A stereo projector from Barco or Christie is more expensive than two off the shelf 1-chip DLP systems, possibly even when modified for active stereo. The double input bandwidth is a strong argument as well.

Using one projector: The best, and most affordable, solution would be a single chip DLP with a double pixel pipeline.

3.1. First Version: Double projector solution

As we have shown in [Hop05] it is indeed possible to generate full quality images for only one half of the frame time, which had been assumed by Develbiss in [DS02]. The reason is that DMDs are now operated with double data rate (DDR) instead of SDR RAM. The number of colors can be traded for update rate, only their product is limited by the mirror speed. With 24-bit colors on SDR DMDs, some people experience color flicker at low brightness levels, or rainbow effects from slow color wheels. With DDR DMDs the color space is now 30 bit and the flicker is greatly reduced.

To generate the colors with the on/off micro mirrors, in the simple case the color bits are weighted according to their exponent. So the most significant bit, maybe bit 7, takes $\frac{1}{2}$ of the frame time, then bit 6 takes $\frac{1}{4}$, and so forth. In reality, color sequence generation is a very difficult process as bits are split through the frame time to achieve a perceptually better distribution of the light flashes. But when an SDR color sequence is used with a DDR DMD at double speed, a high-quality 24-bit image can be shown $\frac{1}{2}$ of the frame time.

As we stated in [Hop05] this can be used to build a DLP

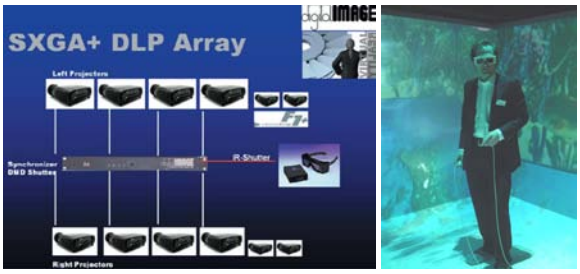

Figure 8: *Immersive 4-sided surround projection system for VR applications (*CAVE*) using a synchronized DLP projector array. A prototype called "DAVE" was built in 2004 at the TU Braunschweig, Germany.*

stereo system with a pair of coupled projectors. One projector blanks the RAM ("*electronic shutter*") and shows black while the other displays an image, and for the 2nd half they exchange their roles. The synchronization makes sure that the formatters operate at the same data rate and phase for all connected projectors, which we achieved by synchronizing the output of the scan conversion buffers. The main difficulty is to decouple the scan converter (here LEHK-II) and its VRAM from the memory on the formatter board. The scan converter digests the input signal and performs the scaling, scan line and frame rate conversion. This unit then drives the formatter with a fixed frame rate, usually 60Hz. This leads to a synchronized output to the formatter board and, thus, to a synchronized operation of all connected DMDs. All color wheels operate at the same speed and the same phase.

Figure 7 shows a color test image of a modified projector of a double projector solution running with 120Hz, 50% shutter closed, with gamma correction circuit. The image was shot through a rear projection screen and is therefore slightly distorted.

3.1.1. Building immersive CAVE-like Systems

The presented two projector solution has been tested in many installations. A very interesting aspect of this solution is that also more than two projectors can be coupled. This allows for immersive and semi-immersive projection systems, for instance 2-segment or 3-segment power walls. Good experiences were also made with an L-shaped setup with four projectors. A much more ambitious 8-projector CAVE-like system was realized in Braunschweig (Figure 8). The independent inputs made it possible to use 8 PCs and to double the 3D performance compared to normal active solutions driven by a single graphic board.

However, some issues remain. The black levels of both projectors are added, which reduces the contrast, and using two lamps results in color differences. The two images of the pairs could not be made to fit exactly on the screen since the DMDs were apparantly not exactly co-planar.

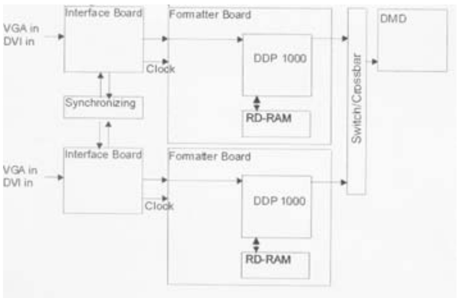

Figure 9: *Two formatters driving a single DMD Chip*

Figure 10: *(a) digital IMAGE Series 611 active projector, (b) back with touch panel*

3.2. Second Version: Single Projector Stereo

Since the DMD is a digital device it may be shared by two image sources by switching data bits. A high resolution SXGA DMD with 1280×1024 pixels has a 128 bit bus operating at 60 MHz, with data on rising and falling edges of the clock signals, resulting in a data rate of approx. 120 MHz. Newer SXGA+ DMDs with 1400×1050 pixels use a LVDS mechanism with ≥ 64 bits at up to 200 MHz.

Our idea is to connect the formatter not directly to the DMD as in [SOA91], but to a high speed switch similar to a memory crossbar (Figure 11a). Switching between two (or even more) formatter outputs enables us to display different images in each turn of the color wheel within the same frame. Since the input images are synchronized, to switch between the images is uncritical. The DMD looks like a simple RAM to the formatter, and as all formatters perform only write operations, the switch is completely invisible to them.

Details are shown in Figure 9. Two inputs are each fed into an interface section where they are scanned and scaled, and stored in two memories. They are transferred synchronously to the Texas Instruments formatter engines yielding two different but synchronous PWM sequences to drive one single DMD. In between is our high speed switch that routes 5.2 Gbit/s between the two mainboards, 120Hz×30bit×1400×1050 pixel. The switch is toggled synchronously to the color wheel at 120 Hz, alternating the PWM sequences between the two formatter engines for each color wheel turn. Note that the shutter glasses also have to be synchronized. This is controlled by a *synchronizer* cir-

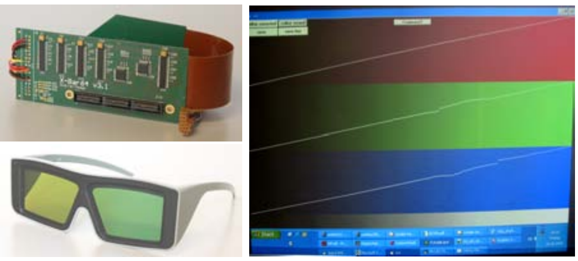

Figure 11: *Left: (a) High-speed switch to combine two pixel pipelines with 5.2 Gbit/s, (b) next generation active glasses. Right: (c) color measurements*

cuit with a freely programmable timing sequence to support different types of applications, among others the shutter glasses. It can also be connected to the synchronizers of other projectors, in order to build up a *synchronized projector array*.

The finished stereo projector. The case shown in Figure 10 contains the mainbords (scaler and formatter) of two projectors, stacked one upon the other. This is clearly visible at the back of the projector (10b) providing all the input connectors. In-between the two formatters and the DMD is mounted the high-speed switch from Figure 11a. The optical system is not modified at all and, thus, all optical parameters are identical to those of the original projector.

3.3. Conclusion

The result is a portable 1-chip stereoscopic DLP projector with dual-headed input and a single lens. We claim that it has huge advantages over other solutions, which becomes clear when checking the user wish list from section 1.6.

- **Easy mechanical setup**
  The single lens eliminates inter-projector adjustments.
- **Avoid non-standard materials**
  Even a simple wall can be used for a 3D projection!
- **Comfortable glasses**
  We have found a manufacturer of active glasses that are comparable to passive classes w.r.t. comfort, see Fig. 11b
- **Avoid using filters if possible**
  No degradation in brightness, contrast or color.
- **Even color degradation**
  The same lamp and optical system is used for both eyes.
- **High resolution and brightness**
  The series 611 provides SXGA+ 1400×1050 Pixel, a full 1900×1080 with 5000 AL for 3D cinema will come next.
- **Cost**
  Our projector is cheaper than a 3-chip DLP, but still more expensive than a normal 1-chip projector. The operating costs are low since only one standard lamp is used. Hopefully mass production will make the cost come down.
- **Practical usability**
  With a weight of 7 kg the projector is portable. The operation is slightly more difficult than a 2D projectThe result is a very portable projector for high resolutions to build any kind of virtual environment.or, mainly because of missing standards for 3D, but the user is supported by a touch panel (Figure 10b).
- **Input bandwidth**
  In our experience the dual-head input is the ultimate solution for 3D data input due to its quality, performance, ease of programming, and no genlocking required.

4. Patents and Acknowledgements

The presented solutions are part of international patents held by digital IMAGE.

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