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360-degree Multi-Viewer Autostereoscopic Tabletop Display with Omnidirectional Dynamic Parallax Barrier and Novel Time-Multiplexed Directional Backlight

Hagen Seifert, Quinn Smithwick; Disney Research; Los Angeles, CA

Abstract

The goal of this project is to develop an autostereoscopic tabletop display for multiple viewers freely positioned around the display. 3D content is produced by an omnidirectional dynamic parallax barrier display using dual layer transparent LCD panels. Time multiplexing the parallax barrier's period and orientation, and the use of a directional backlight allows for displaying 3D content 360° around the table to multiple tracked viewers. The novel directional backlight provides precise addressability of a large number of views using a hemispherical mirror to collimate light from a concentric outwards facing hemispherical LED array.

A prototype was built using two 27" 2560×1440 pixel resolution LCD displays with 144Hz refresh rates. Interactive content and dynamic parallax barriers are rendered in a Unity 3D game engine based upon viewer positions obtained from a Vicon tracking system and a Kalman filter. The addressable backlight consists of 216 LEDs, addressable in 36 rows 10° apart placed on a transparent 38cm (15") wide hemisphere inside a 76cm (30") hemispherical concave mirror.

Introduction

360-degree autostereoscopic tabletop displays enable the display of three-dimensional (3D) content sharing the same space as real world objects on the table. Multiple viewers around the table can observe and interact with the same virtual objects in a very natural way, which has a wide range of possible uses, including collaboration in computer-aided design, teaching, and entertainment.

Many commonly used concepts for vertically oriented autostereoscopic displays cannot be applied to 360-degree tabletop displays. Lenticular lens and static parallax barrier based multi-view displays can only provide parallax in one direction; integral 3D displays using lenslet arrays offer parallax in two directions, but like lenticular lens and static parallax barrier based displays suffer from low viewing angles and periodic view repetition [1]. A lenticular based Tracked Autostereo Tabletop with viewer tracking and multiscopic viewpoint reprojection overcomes the lenticular display's inherent limitations, such as horizontal-parallax-only perspectives, limited field-of-view and repeated viewzones, but cannot produce a 360-degree display due to the fixed orientation of the lenticles [2].

A well explored approach to 360-degree autostereoscopic displays is the use of high speed projectors that generate a large number of views in combination with rotating anisotropic projection screens to redirect the views in the appropriate direction. In some of the designs the rotating projection screen intersects with the displayed volume [3], [4], [5], others use a flat screen to create a tabletop display [6][7][8], [9] . Butler et al. used a well-known optical illusion using two facing parabolic mirrors to re-image the rotating screen above the table surface [10]. Common drawbacks of these systems are the low bit-depth of all displayed images due to the nature of the high speed binary image projectors, as well as the fast spinning projection screens.

Light field displays with a large number of views at full resolution and bit-depth can be achieved using an array of projectors [11] [12]. Using a special conical shaped diffuser, this approach was adapted to a 360-degree tabletop [13]. The obvious drawback of these designs is the high cost associated with the required large number (hundreds) of projectors. Furthermore, the calibration of the projectors can be challenging.

Autostereoscopic displays based on stacked LC display layers with common backlight offer more flexibility compared to using fixed optical elements such as lenticular sheets and parallax barriers.

Peterka et al. created a dynamic parallax barrier using two LC layers called Dynallax [14]. The top layer was used to display a parallax barrier whose parameters such as the barrier period and offset could be adapted dynamically to the tracked viewer position.

A team at the MIT Media Lab proposed multiple autostereoscopic displays based on two or more stacked LC layers with uniform or directional backlight that exhibit two dimensional parallax at moderate viewing angles without tracking [15][16][17].

Nashel et al. use a randomized hole pattern as a parallax barrier enabling multiple tracked viewers in arbitrary locations [18]. This concept was then adapted for a tabletop display [19].

For the use in the 360-degree tabletop display proposed in this paper, we extended the dynamic parallax barrier by Peterka et al. to additionally change its orientation according to the viewer position.

While Peterka et al. also proposed a dual period barrier to support two simultaneous viewers, this would not work in a 360-degree display, where the direction of the parallax varies per viewer. Instead, we combined the dynamic parallax barrier with a novel directional backlight with a large number of individually addressable views, which allows for up to four viewers through time-multiplexing.

Omnidirectional Dynamic Parallax Barrier

A tabletop omnidirectional dynamic parallax barrier display can show autostereoscopic content to a single tracked viewer anywhere around the table.

Background

A parallax barrier is a mask consisting of a series of slits that is placed in front of an image source in a way that each part of the image is visible to only one of the eyes while being occluded to the other, as illustrated in figure 2-1a). By placing images from a left eye viewpoint into the stripes visible to only the left eye and vice versa, an autostereoscopic 3D effect can be achieved.

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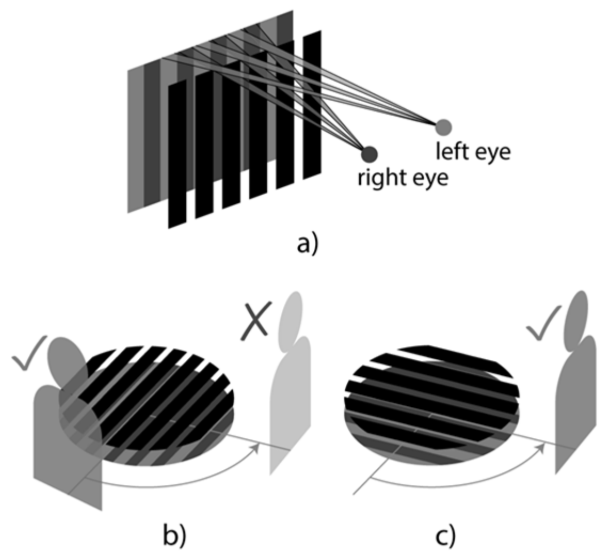

Figure 2-1. *a) The parallax barrier, a mask of opaque and transparent stripes, occludes a different part of the image source for each eye, so that in this example the right eye sees only the dark gray stripes while the left eye sees only the light gray stripes. b) When used on a tabletop display the viewer's orientation relative to the display changes as they walk around the table. As the parallax barrier only works as long as the offset of the eyes is approximately perpendicular to the slits of the barrier, its orientation has to dynamically adjust to the viewer position.*

A static image source and mask create a set of periodically repeating views at a distance which is determined by the distance of the mask to the image source and the barrier period of the mask. By using an LCD as image source the lateral viewing positions can be adjusted to a tracked viewer, as shown by Sandin et al. with their Varrier display [20]. However, the distance of the viewer to the display is still strongly limited by the fixed distance and period of the parallax barrier. The Dynallax display by Peterka et al. uses a second LC layer as a dynamic parallax barrier, which allows for changing the barrier period for a much wider range of viewing distances [14].

For the use in a tabletop autostereoscopic display, the dynamic parallax barrier concept has to be further adapted, since the barrier only works if the offset between the eyes is approximately perpendicular to the slits of the barrier. If the viewer on the left in figure 2-1b) were to move 90º around the table while the orientation of the parallax barrier remained constant, both eyes would see the same parts of the image source and the autostereoscopic effect would vanish.

In our implementation, the orientation of the parallax barrier always follows the viewer making it possible to see the 3D content from anywhere around the table (figure 2-1c)). We call this the omnidirectional parallax barrier.

System Parameters

A parallax barrier is defined by a set of parameters, which are either fixed or can be adapted dynamically. In the dynamic parallax barrier implementation, the only fixed parameter is the distance t between the two LC layers. The dynamic parameters are the period, duty cycle, angular orientation, and lateral shift of the barrier and the image source.

The duty cycle of the barrier, defined as the fraction of the barrier period that is opaque is chosen as 0.75. This means that the image source will display black stripes between the stripes containing the image information for each eye, which minimizes crosstalk. This also means that the minimal barrier period is equal to four times the pixel size, since otherwise the width of the slits would become less than one pixel.

Formula (2) from [14] connects the normal distance of the viewer from the screen z_{opt}, the distance between the LC layers t, and the barrier period p:

$$z_{opt} = \frac{2t(e-p)}{p} \quad (1)$$

where e denotes the interocular distance (typically 63.5mm). We can see, that the minimal barrier period sets a limit to the maximum viewer distance $z_{opt,max}$, which means that the distance between the LC layers has to be chosen accordingly. The barrier period is calculated every frame from the above equation based on tracking data of the viewer.

In the omnidirectional parallax barrier, the orientation of barrier and image source is chosen so that the central slit of the parallax barrier always points at the viewer. This way the lateral shift of both the barrier and image source can be left constant relative to the display center. Finally, the period of the image source p' can be calculated using

$$p' = p\,\frac{(z_{opt}+t)}{z_{opt}} \quad (2)$$

which simply follows from the intercept theorem.

Time Multiplexed Directional Backlight

A directional backlight is a backlight that makes the displayed content visible from certain viewing positions, while the screen appears black from others. By quickly switching the content and backlight between different viewer positions, multiple independent views can be displayed simultaneously. For a 360-degree tabletop display, the backlight must be able to individually address a large number of viewing positions all around at high viewing angles.

An advantage of time-multiplexing over spatial-multiplexing for autostereoscopic displays is that the full panel resolution can be preserved. However, the number of views that can be multiplexed at one time without visible flickering is limited by the refresh rate of the panel used. By combining spatial multiplexing in form of the dynamic parallax barrier and temporal multiplexing in form of the directional backlight, our display can provide autostereoscopic content to up to four viewers simultaneously.

The novel time-multiplexed directional backlight presented in this paper can address an arbitrarily large number of viewing positions 360° around the display, covering a solid angle of up to 2π steradian (one hemisphere). This is achieved using a hemisphere mirror to focus the light coming from light sources positioned pointing outwards on a smaller transparent hemisphere.

Background

Multiple approaches of time-multiplexed directional backlights for autostereoscopic displays have been demonstrated. A two-view time-multiplexed directional backlight can be achieved using a special light guide with a prism sheet and one light source at either side [21][22], [23]. This allows creating an autostereoscopic display at full panel resolution that is only slightly thicker than a regular 2D display. However, the 3D effect only works at one specific viewer position.

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Another approach uses an LCD panel with uniform backlight and a lenticular lens array to create a multidirectional backlight [24], [17] Disadvantages include the low light output and low viewing angles typical for lenticular lens based displays.

Hayashi et al. used an elliptic mirror with two light sources two create a two view directional backlight [25].

None of the above backlight systems can provide the number of views and viewing angles necessary for a 360-degree tabletop display.

Concept and Simulation

At small apertures, a spherical mirror of radius r_m can be locally approximated as a parabolic mirror with a focal length of

$$f = \frac{r_m}{2} \tag{3}$$

Therefore light reflected on the mirror coming from a light source at half the radius of the sphere will be approximately collimated. Placing the light source further towards the center of the sphere at a distance d_o from the surface will focus the light at distance obeying the mirror equation:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \tag{4}$$

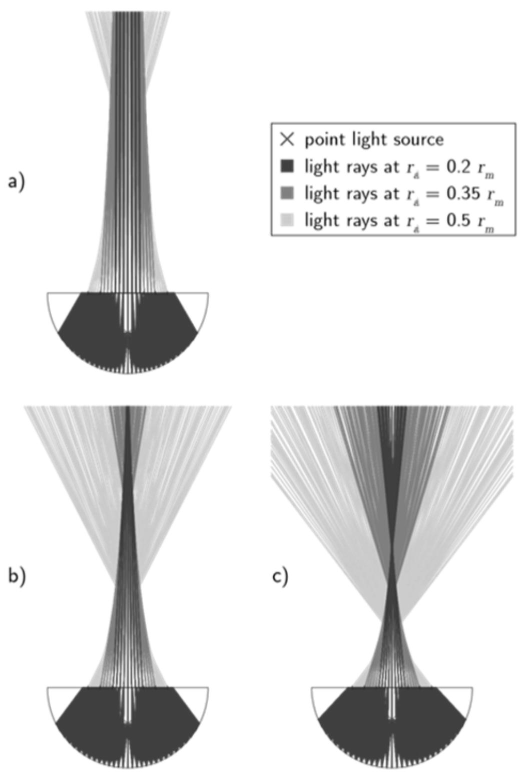

Figure 3-1. *Ray tracing of light reflected on a hemisphere mirror with radius* r_m *from a point light source pointing downwards at a distance of a) 0.5* r_m *b) 0.45* r_m *c) 0.4* r_m *from the sphere center. The light passes through three different circular apertures with radii* r_a*. It can be observed that a smaller aperture leads to a better focusing of the ray.*

In reality, the focal length varies for larger apertures, so that outer rays are focused closer to the mirror than center rays. Choosing a smaller aperture will result in a better focusing of the rays, at the expense of a smaller display area that can be backlit using the same hemisphere mirror or a larger mirror that is required for the same display size. Figure 3-1 shows ray tracing of light originating from light sources on the central axis of the hemisphere mirror at various distances and apertures.

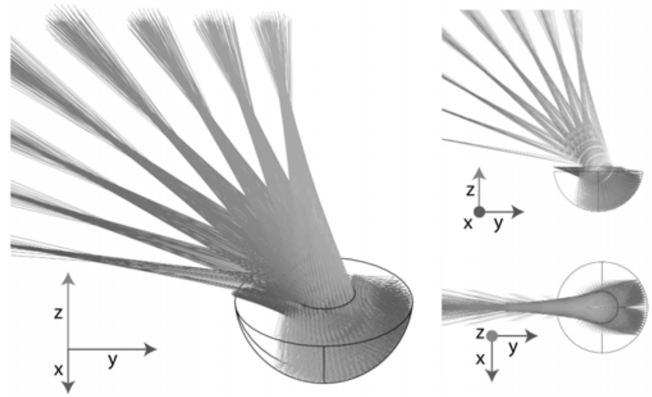

Figure 3-2. *Ray tracing of eight light sources pointing outwards at 0.45* r_m *from the center of the sphere at the same horizontal angle and vertical angles in steps of 10° from 10° to 80° with an aperture of 0.35* r_m*. Each light source addresses a separate vertical view of the display.*

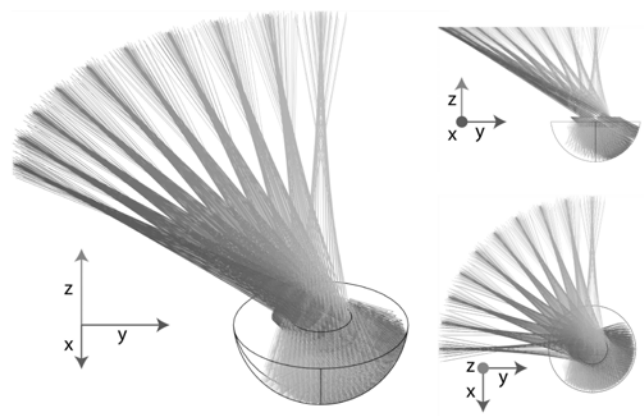

Figure 3-3. *Ray tracing of ten light sources 0.45 rm from the center of the sphere at the same vertical angle of 30° and horizontal angles in steps of 10° from 0°-90° with an aperture of 0.35 rm. Each light source addresses a separate horizontal view of the display.*

As a result of the symmetry of the spherical mirror, the same imaging properties apply for light sources on any axis through the center of the sphere. By using multiple light sources a directional backlight with an arbitrary number of views can be achieved. Figure 3-2 shows ray tracing with light sources to address 8 different views in the same horizontal direction that are 10° apart vertically. Conversely, figure 3-3 shows addressing 10 views at the same height, 10° apart horizontally.

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By choosing an appropriately small aperture in combination with a sufficiently high number of light sources, an angular resolution high enough to separately address the eyes of a viewer could be created. However, since our display uses a dynamic parallax barrier for each viewer, only a less accurate backlight is required, which allows us to use a smaller number of light sources and higher aperture.

Protoype

We built a prototype that can show autostereoscopic 3D content on a circular tabletop displaying area with a diameter of approximately 14” (35.6cm). It can be seen in figure 4-1.

It uses two regular 27” (68.5cm) LCD displays whose backlights have been removed, a Vicon motion tracking system, and a directional backlight which comprises a reflecting 30” (76.2cm) diameter hemisphere and 216 high power LEDs.

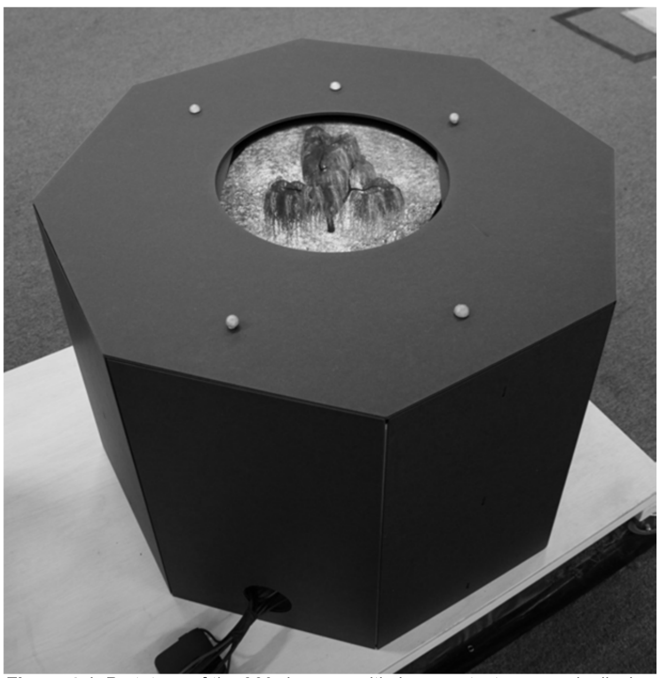

Figure 4-1. *Prototype of the 360-degree multi-viewer autostereoscopic display with a display diameter of approximately 14” (35.6cm) for up to four viewers. Five retroreflective spheres are used for tracking the display location. The parallax barrier is disabled for the photo.*

Dynamic Parallax Barrier Display

Two main criteria influenced our choice of LCD displays to be used as a basis for the dynamic parallax barrier display: First, since the effective horizontal resolution of the display will be divided by the period of the parallax barrier, a high native resolution of the panel is favorable. Second, a high frame rate is necessary for time-multiplexing for multiple viewers, since it will be divided among them.

We therefore use two ASUS ROG SWIFT PG278Q 27” displays with a resolution of 2560×1440 and a frame rate of up to 144Hz. The case and backlight are removed from both displays, as well as the front diffusing film from the upper display which is used to display the parallax barrier. The distance between the two displays is set to 9mm, which, using equation (1) led to a maximum vertical viewing distance of 120cm above the display. At this distance the barrier period is exactly 4 pixels, which, when using a duty cycle of 0.75, represents the lowest resolvable barrier period. The minimum viewing distance is calculated accordingly to Peterka et al. as the distance where the barrier period increases to 12 pixels, which results in 39cm [14].

When both displays are stacked with the same orientation, their pixel grids and color filters lead to a strong moiré pattern (a macroscopic repeating pattern of darker and lighter areas). This is be alleviated by rotating the upper display by 18° compared to its lower counterpart (see figure 4-2). Finally, a half wave plate is placed between both displays to rotate the linear polarization of the light coming from the front polarizer of the lower display to match the orientation of the back polarizer of the top display.

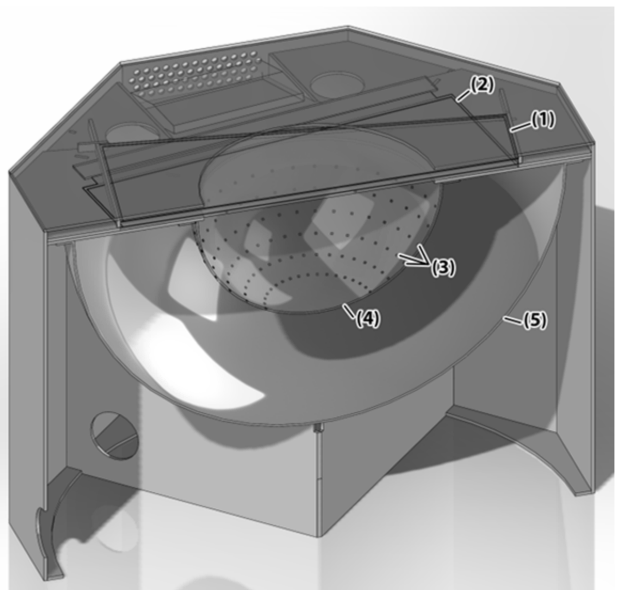

Figure 4-2. *Cutaway view of the display prototype. (1) Upper (parallax barrier) display; (2) lower (image source) display 18° rotated; (3) high power LEDs facing outwards; (4) transparent hemisphere holding the LEDs; (5) reflecting hemisphere.*

Directional Backlight

We used a 30” (76.2cm) diameter acrylic dome that was painted from the outside using mirror spray as a hemisphere mirror for our directional backlight. 216 LEDs were attached on the outside of a 15” (38.1cm) transparent acrylic dome pointing outward. A circular aperture with a diameter of 14” (35.56cm) limits the usable area of the display. Placing the LEDs exactly half of the its radius away from the mirror doesn’t allow for precise focusing of the light, but it keeps the light from diverging for the longest distance from the display, especially at large apertures (compare figure 3-1a)). The LEDs are placed 10° apart in spherical coordinates, at vertical angles ranging from 15° to 65°.

Each of the 216 LEDs has a maximum power dissipation of 2W and provides a luminous flux of 259lm. For the use in a tabletop display, the directional backlight only needs to be able to separately address angles around the vertical axis, assuming that two viewers will always stand next to, but never behind each other. Therefore, the LEDs are addressed in 36 strings of six LEDs each. Every string contains a current limiting resistor and an NMOS

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transistor to turn it on or off, and is connected to a 24V power supply. The 36 NMOS transistors are controlled by an Arduino Mega 2560 microcontroller board.

The backlight and the dynamic parallax barrier display are held together by a case made of laser cut 5mm thick foamcore board. The setup can be seen in a cutaway view in figure 4-2.

Tracking, Synchronization and Time-Multiplexing

A Vicon motion capture system was used to track the positions of the viewers relative to the display. It uses high speed infrared cameras to track retroreflective balls or infrared LEDs with millimeter accuracy and low latency. This requires each of the up to four viewers to wear glasses frames with distinct arrangements of three to four 1cm sized retroreflective balls. An additional tracker is placed on top of the tabletop display as a reference location as seen figure 4-2.

The tracking data is received by a PC running a 3D application based on the Unity game engine (Version 5.1). It calculates the relative eye positions of the viewers from the tracking data, renders a scene from their viewpoint and controls the parallax barrier. For time-multiplexing multiple viewers it iterates through their positions one frame at a time. Furthermore it sends the angles required for the directional backlight to the Arduino microcontroller board via a USB connection. The refresh rate of the displays is limited to 120Hz by the driver of the Nvidia graphics card. In order to maintain flicker free time-multiplexing it is important that the application maintains a stable 120Hz frame rate at all times.

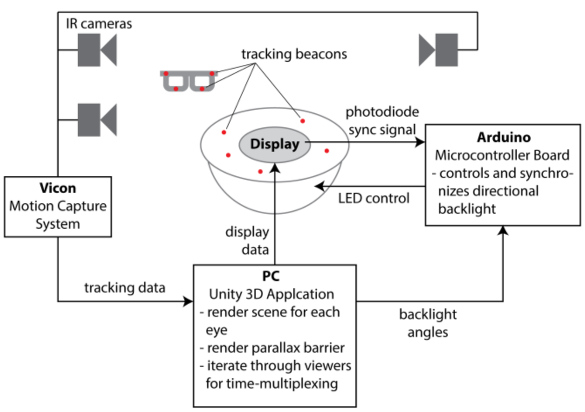

Figure 4-3. *Block diagram showing the devices and data flow involved in the control of the 360-degree multiviewer autostereoscopic tabletop display.*

The directional backlight needs to be precisely synchronized with the displays. Measurements have shown, that the LCD panels continually update from one frame to the next line by line, which takes approximately 7ms from top to bottom. This leaves a time window of only a bit more than 1ms where a complete frame is displayed on the display and the backlight can be turned on. In order not to rely on the serial connection from the computer to the Arduino for the timing, two LED-photodiode pairs are attached on the unused outer part of one of the LCD panels which sense when the display turns transparent or opaque. For detecting frame changes, a square underneath one of these photodiodes is switched between transparent and opaque each frame. The square below the other photodiode is switched transparent only when the content for the first viewer is displayed in time-multiplexing.

An overview of the mentioned devices and the data flow between them can be seen in the block diagram in figure 4-3.

Results and Discussion

In our implemented prototype, we observe that the aperture and the stacked LCD panels are generally evenly illuminated by directional backlight for each set of light sources and angular directions. There are some nonuniformities in the illumination due to the inconsistencies in the sprayed mirror coating and shadows cast by the LEDs and their wiring as the light passes back through the inner hemisphere. However, multiple light sources are illuminated at any one time, smoothing the inconsistencies and softening the shadows. Transparent conductors, PCBs, and microLEDs are additional ways that could ameliorate any shadowing. There are additional changes in the display luminance when viewed along the LCD panels' long axes, due to the characteristics of the LCD panels off-axis; however this could be compensated for in the backlight's LEDs corresponding to those viewing angles.

Even with the high speed, low latency tracking provided by the Vicon system, lag is apparent as increased crosstalk between both eyes as a viewer moves around the table, caused by the delay with which the narrow viewing positions created by the parallax barrier follow the eye positions. With the inclusion of motion prediction of about 50ms using a Kalman filter, viewpoints are rendered consistently and smoothly with the viewer's location even while the viewer moves. The illumination does not flicker as the viewer changes position around the display, since the illumination headbox is larger than the viewer's head and the illumination switching occurs at the headbox edges. The directional illumination does not need to aim for each eye; the illumination only needs to cover the head position, while the parallax barrier provides the stereoscopic views to the appropriate eye.

The angular resolution of the directional illumination ensures each viewer only sees his/her appropriate image on the screen at one time. Two viewers standing at least 45° apart see independent images, as their illumination headboxes do not overlap (figure 5-1). However, a viewer cannot stand in front of another viewer, as they will both see each other's 3D images; though this is not a particularly limiting constraint.

By using 144fps LCD panels, we quickly multiplex oriented parallax barriers and 3D imagery between the multiple viewers. At standing heights above the tabletop, the pitches of the parallax barriers are fine enough that they are visually unobtrusive and easily ignored. With each additional viewer, each 3D image gets dimmer due to the light being multiplexed and divided amongst the viewers. Even for four simultaneous viewers, each viewer sees dynamic interactive 3D imagery smoothly rendered and displayed at 30fps, although flicker starts to become apparent. The 3D scene is consistently rendered for each viewer's viewpoint, so all viewers may point to the same common point and agree to its location in 3D space.

The 3D imagery is clear and extends above and/or deep into the table. The diameter of the aperture is large enough that 3D objects several inches tall may appear in the middle of the table without being unnaturally clipped by the edge of the aperture. Window violations still may occur for taller objects or objects near the screen edge, however this is common to all view-based tabletop 3D displays. Because stereoscopic pairs are presented to each viewer, very deep 3D scenery of a few feet can appear below the display, and the clipping by the aperture and occlusion by physical objects above the display is natural.

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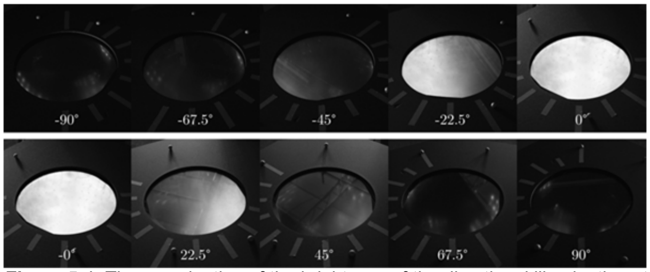

Figure 5-1. *The examination of the brightness of the directional illumination at nine different angles from -90° to 90° from the addressed viewer position shows that two viewers should stand at least 45° apart to see independent images. Limited backlight direction contrast leads to crosstalk between different viewers.*

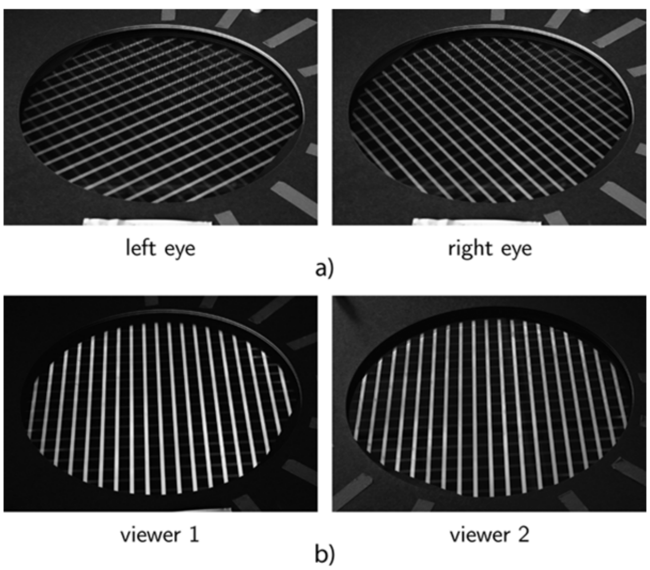

Figure 5-2. *Examination of crosstalk from different sources. a) Orthogonal lines are displayed to both eyes to demonstrate crosstalk caused by the parallax barrier. b) Vertical lines are displayed to two viewers 90° apart. The observed crosstalk is caused by backlight direction contrast as well as LCD rolling shutter.*

There are three main sources of crosstalk: parallax barrier quality, backlight direction contrast and the LCD rolling shutter. The opacity and alignment are primary causes of crosstalk in parallax barrier displays, and mainly affect each viewer independently (figure 5-2a)). Although transparent regions in LCD panels are greatly attenuating, the opacity of the black regions displayed on LCD panels is generally excellent, producing good quality parallax barriers. A properly orientated, high quality and accurate quarter wave plate is required to ensure the polarization is correctly rotated between the two panels, and ensure the parallax barrier works as intended. The use of a high quality tracking system, with proper calibration of it and the parallax barrier parameters, also ensures the parallax barrier is accurate for each viewpoint.

Imperfect reflection and scattering from the mirror's and the LED array's hemisphere's creates a diffuse background illumination of the dual layer LCD panels observable to all viewers (figure 5-1). This appears as crosstalk between viewers (figure 5-2b)). This diffuse glow is dim and non-directional, easily overwhelmed by the bright directed illumination intended for the viewer. The orientation of the parallax barrier during unintended viewing periods is incorrect to provide coherent 3D views, and changes rapidly as it switches between viewers; thus it generally appears as dim background noise.

Another source of inter-viewer crosstalk is during transition periods in the LCD's rolling scan when the displayed image is a combination of two viewer's parallax barriers and content. The use of a 144fps display allowed us to have a single complete image occupy the entire frame at some period of time. Using a LED/photodiode pair and codes in the corners of the LCD image, we could synchronize the backlight to only flash when the entire frame was a single image, thus reducing inter-viewer crosstalk. Another embedded image code and photodiode pair allowed us to ensure proper pairing of backlight direction and parallax barrier. A graphics card and software that supports quad buffering (ensuring four sequential frames buffers are consistently cycled through) could remove the need for the LED/photodiode pairs and embedded image codes; however, in this prototype, Unity 3D does not support quad buffering.

Conclusion

The main benefits of our display include a flat 3D tabletop surface, no complicated or moving parts, adjustable and simple-to-compute parallax barriers to provide 3D views to multiple viewers 360 degrees around the tabletop display, and a novel 360 degree directional backlight that provides large, even, collimated illumination that can be rapidly steered.

The multi-viewer autostereoscopic tabletop display systems with spinning elements or a hundred projectors have demanding hardware and software (rendering algorithms) requirements, especially considering many displayed views are not seen by the viewers. Scaling these displays is expensive and/or difficult, due to rapidly moving parts or a large number of components. Our display is only practically limited by the size of the two LCD panels and has no moving parts.

The Tracked Autostereo Tabletop used a flat horizontal lenticular display; however, the lens orientation was necessarily fixed, so even with proposed directional backlighting, this system only facilitates two oppositely facing viewers (in the same axis as the lenticels' axes). Our dynamic parallax tabletop uses an LCD panel to make parallax barriers of almost any direction and pitch we desire. With such an omnidirectional parallax barrier, objects placed on the table are in the same 3D space as content that is displayed. This and the ability to handle multiple simultaneous viewers enable collaborative interactive 3D tabletop applications.

The Dynallax, which also uses a dynamic parallax barrier but for an upright display wall, only works as long as the head orientation remains approximately perpendicular to the fixed parallax barrier orientation. Our tabletop display has a dynamic omnidirectional parallax barrier that works with any viewer position and head orientation.

Content adaptive parallax barriers (and more general multilayer lightfield/compressive displays) require complex computation. Every mask includes multiple views, with horizontal and vertical parallax, which leads to artifacts similar to crosstalk in every view. Furthermore, the content adaptive parallax barriers are so far not adapted to the viewer position and therefore have low viewing angles around the central viewing position. Traditional dynamic parallax barriers such as used by Dynallax and our omnidirectional parallax barrier proposed here are easy to compute and only need to encode the two views necessary for the two eyes of each viewer. The computations are simple enough to be implemented real-time directly in the commercial Unity 3D

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gaming engine, so that 3D games and interactive applications can be created for the tabletop display easily. The use of only two views per viewer results in a 3D display with low crosstalk and large view angles. Stereo pairs may present very deep 3D scenes, limited mainly by vergence-accommodation conflicts. By contrast, multiview displays have a limited depth range due to their coarse angular sampling resulting in interperspective aliasing;

Many directional backlights (such as convex lens or 3M directional film) can only distinguish between two viewing positions for autostereoscopic displays, and only have a narrow view zone. Other approaches use a per pixel directional backlight instead of time multiplexing, which reduces the available spatial resolution, but allows more views to be shown simultaneously (e.g. by using a prism array or diffraction gratings).

Future work includes increasing the number of viewers, the quality of the 3D imagery, and the simplicity of the tracking system. We could increase the number of viewers by creating more than two views with each parallax barrier, or by replacing the linear parallax barrier with a random hole pattern. The directional backlight would produce a wider collimated light, so multiple viewers could be served per displayed frame, for eight or more viewers around the table.

Using smaller and a larger number of LEDs would produce a higher resolution directional backlight. This could allow us to direct images directly to each viewer's eye, rather than relying on the parallax barrier to provide stereo separation. Without a parallax barrier, we could achieve brighter, higher resolution 3D images, but only for 2 or 3 viewers using the current 144 fps LCD panels.

We used a Vicon system to provide high quality, high speed tracking of the viewers' locations. However, it required the viewers to wear markers, and still exhibited some latency perhaps due to network traffic. The Kalman filter helped to accurately predict the viewers' locations and reduce the tracking latency. The Kalman filter worked well enough that it could be used with a less expensive, markerless tracking system to provide a more affordable and compact system for use with the display hardware.

The goal of this project is to develop an autostereoscopic tabletop display for multiple viewers freely positioned around the display. Our solution uses an omnidirectional dynamic parallax barrier display in conjunction with a novel directional backlight. The parallax barrier's period and orientation is adjusted for each tracked viewer. The directional backlight provides precise addressability of a large number of views using a hemispherical mirror to collimate light from a concentric outwards facing hemispherical LED array. Time multiplexing the parallax barrier content and the backlight illumination direction provides independent 3D stereoscopic content for each of the four viewers. Multiple viewers around the table can observe and interact with the same virtual objects in a very natural way, which has a wide range of collaborative design and entertainment applications.

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Author Biography

Hagen Seifert received his BSc and MSc in Electrical Engineering and Information Technology from the Swiss Federal Institute of Technology Zürich (ETH) in 2013 and 2014. In 2015 he worked as a Project-Hire Research Associate at Disney Research in Los Angeles, California, following his interests researching 2D and 3D display technologies and applications.

Quinn Smithwick is a Senior Research Scientist at Disney Research researching novel displays. He received his engineering PhD from the University of Washington for research on the nonlinear modeling and control of resonant fiber scanners. His postdoctoral research at Harvard Medical School was on the development of a transportable scanning laser ophthalmoscope. His postdoctoral research at the MIT Media Lab was on the development of holographic video displays. He joined Disney Research in 2010.