Constructing an Autostereoscopic Display using Lenticular Optics

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Abstract—**an autostereoscopic display is created from a standard LCD monitor using a pre-fabricated lenticular sheet. The lenticular sheet allows the vertically interlaced images to be sent to the corresponding eye of the viewer using the specific optical properties of the convex micro-lenses on the sheet. The display system works with both stereoscopic images and video by post-processing in order to send a properly modulated signal to the display. The monitor resulted in a high extent of crosstalk due to the offset between the pitch of the lenses and the monitor's pixels. An in depth solution is discussed in combating the extreme crosstalk via extensive post-processing.**

I. Introduction

One eye at a time is only capable of perceiving a planar image. 3D viewing is achieved by the use of both eyes to provide each eye with an offset view of a scene which the brain can than interpret its depth. This is known as binocular viewing. The images which the eyes receive from the same scene are offset according to the locations of the eyes. The objective of autostereoscopic viewing methods are to send the corresponding images to each eye of the viewer without the requirement of the viewer to wear or have any elements in front of their eyes to perceive depth.

A. *Paper Objectives*

- Understand how the human visual system perceives depth and what psychological cues exist to present depth to the viewer
- A brief summary on currently used autostereoscopic methods/approaches and types of displays
- An in depth look on how lenticular displays work
- Relating the requirements of the lenticular sheet given a display specifications
- How to physically combine the display panel with the lenticular sheet to create an autostereoscopic solution
- How stereo/3D content will need to be processed before the signal can be sent to the system
- Combating the issue of crosstalk
- Qualitative and quantitative discussion with regards to the results in constructing an autostereoscopic display from a prefabricated lenticular sheet

B. *Brief Introduction to the Proposed Autostereoscopic Display*

This approach in creating a glasses free 3D display out of a standard LCD monitor is an alternate means of viewing 3D content using consumer end displays and a lenticular sheet dependent on the specific display. With 3D content being distributed on a larger scale it is important to evaluate the ability, effectiveness and degree of difficulty in ensuring that standard display devices can be used in order to properly view stereoscopic content.

Lenslet arrays propose using small convex lenses in order to accomplish a means of refracting light to each eye. The similar concept of parallax barriers entails attenuating masks to separate the two images meant for each eye. There are trade-offs with each of these displays as barriers cause attenuation which leads to dim displays and lenslet have a fixed trade-off between spatial and angular resolution (more detail on each will be discussed later) as well as chromatic aberrations. Both of these techniques support a means of perceiving depth using interlaced images. An autostereoscopic display is constructed using a pre-fabricated lenticular sheet to match the necessary specifications of the standard LCD monitor.

II. Background

A. *The Human Visual System*

What causes you to perceive depth when you look at a 2D image? These are known as "depth cues" and can be both monocular and binocular. Monocular depth cues can be expressed as a means of perceiving depth with only one eye open or the same "signal" sent to each eye. When we move to binocular case where we can send a different signal to each eye, there are a variety of ways to perceive depth which we previously could not in a monocular sense. There are limitations of conventional displays. Depth cues we receive from a conventional display are from our perception of relative size and familiar size of an object, perspective, occlusion, texture gradient, shading, and lighting. From these displays we are missing binocular depth cues. These binocular cues allow us to perceive depth by means of proper convergence and stereopsis.

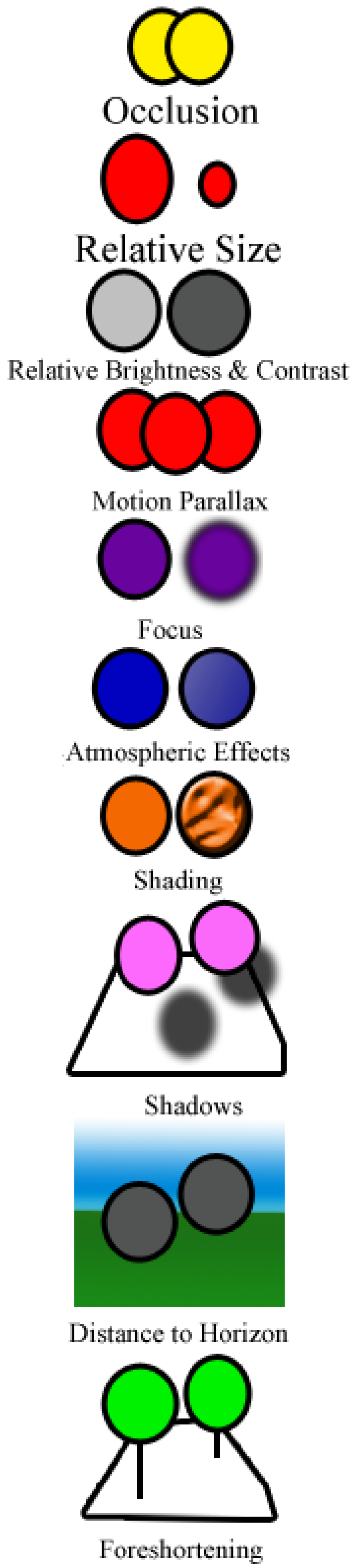

Figure 1 – Types of Monocular Depth Cues

With stereo parallax, also known as stereopsis, each eye sees a different image at a dissimilar angle. The signal which comes from each eye is then processed by the interleaved regions in the "visual canter" of your brain as demonstrated in Figure 2. Two visual pathways are connected from the retina to the brain and with these paths are stereoanomalies which have defects as they contain "neurons sensitive to only crossed or uncrossed disparities. The perception of depth is [considered] to involve responses from both types of neurons. […] In the case where neurons are only sensitive to uncrossed disparities belonging to objects located further away than the Horopter [(see figure 5)] is suppressed in favour [to those] which are [further] away. The individual perceives the close-up information as far away information with a faraway depth [and] when the neurons are only sensitive to crossed disparities, the individual perceives the far away information with a depth close to the eye. Individuals who are stereosblind […] are assumed to be entirely lacking in disparity-sensitive neurons" (Lueder, 3).

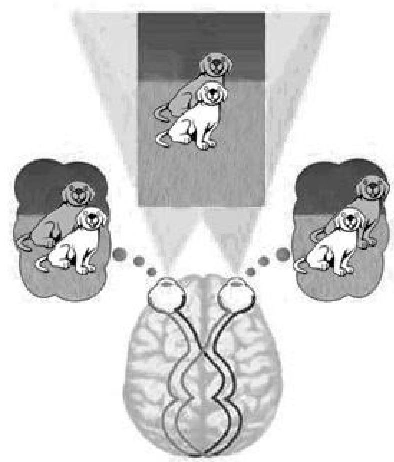

Figure 2 – Simple Demonstration of Stereopsis [Cooper]

Stereopsis is a cue added by 3D displays in which the brain determines depth by observing the scene from two viewpoints.

It is possible to simulate this depth cue by somehow sending a different image to each eye. Typically this is accomplished, particularly in cinema, though passive polarized 3D glasses which uses polarized light projected onto the screen in order to restrict the light that reaches each eye. Unfortunately this polarizing filter concept requires the viewer to wear glasses and this is arguably not the ideal method to view the 3D content.

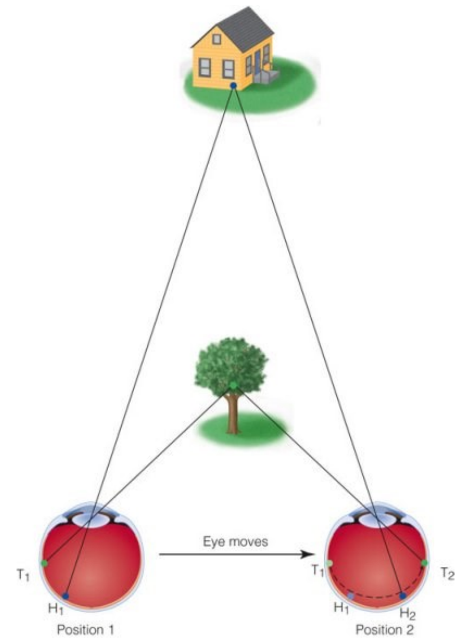

Figure 3 – Movement Parallax
[Steele]

In movement parallax we are able to understand depth in the sense that objects that are closer to us move at a faster rate than object that are further away. In Figure 3, if we looked at this scene and walked to the right, the angle of which we are viewing the tree would change faster or rather to a larger extent than the change in angle of the far away house.

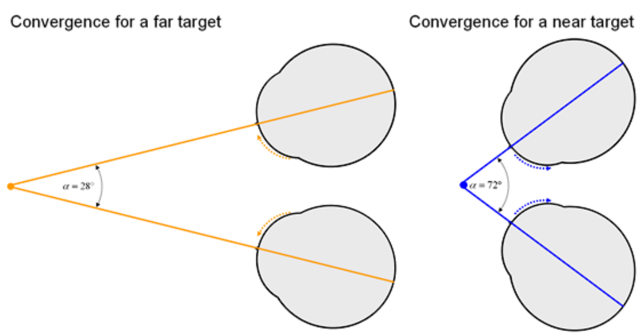

Figure 4 – Convergence
[Waloszek]

In the real world, when objects are closer to us our eyes converge and focus on that object, increasing our angle of convergence. You can prove this to yourself by extending your arm out, looking at the point of your finger and slowly bringing it towards your face. As we focus on objects at infinity, our eyes minimally converge and vice versa. This is related to focus as you focus in different ways depending on how far away things are. In the real world, your brain has a mapping of what convergence should go along with what accommodation (focus). However, new technologies (such as stereo cinema) attempt to break this natural relationship which can be very uncomfortable for some people. Gregg Favalora provides the example of sitting in a 3D movie and an object appears to be coming out of the screen. Your eyes will attempt to cross to make it come into view but they are still focused back at the projection screen.

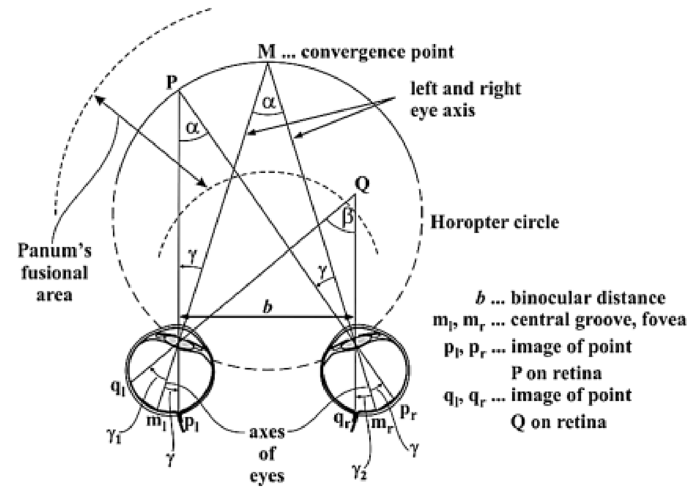

Figure 5 – Horopter Circle
[Lueder, 2]

As seen in figure 5, the Horopter circle serves as a reference of depth. Only in Panum's fusional area can "the fusion of the disparities and the depth perception" work efficiently. This area provides depth perception but "decreases monotonically with increasing magnitude of the disparity. This relationship is called the patent stereopsis" (Lueder, 2). At point Q in the figure 5, which is not on the Horopter circle but instead closer to the eyes but "still in the Panum's area, the disparities on the retina are given by the points ql, for the left eye and q_r, for the right eye with the disparities, for the right eye with the disparities y_l and y_2. These points lie across the fovea on the other side of the retina and exhibit a so-called crossed disparity, while the points farther away than the Horopter have an uncrossed disparity. Their image points corresponding to q_r and q_l for crossed disparities lie on the opposite side of the fovea" (Lueder, 2). When looking at an object which is at point Q, the disparities located at y_l and y_r are no longer equal such that if $y_l - y_r \neq 0$, the disparities "provide information to the brain on how much the depth of Q is different from the depth of the Horopter [circle]. However, how the brain copes with this difference in disparities is not fully known" (Lueder, 2). Depending on the object and how it is moving in relation to the Horopter circle, stereopsis can be lost at a relative distance from the eyes and the fusion of the two views may no longer work. This is called "diplopia" (Lueder, 2). As a result, the brain may try to supress the background information. For the opposite case in which the object is moving away from the Horopter circle, the smaller the disparity and thus the smaller the information with relation to depth provided.

"The smallest still recognizable disparity is 20 arcsec in the spatial frequency range of about 2-20 cycles per degree and the maximum perceivable disparity is 40 arcmin for low spatial frequencies. […] this is also true for temporal frequencies in the dynamic images with a larger sensitivity of disparities for lower temporal frequencies and a lower sensitivity for large temporal frequencies of luminance" (Lueder, 3).

B. *Interocular Crosstalk*

Information which leaks from one view meant for the eye into that of the other eye is known as crosstalk. Crosstalk will often severely damage the quality of the perceived image and can affect the fusion of the two images. Lenticular lenses exhibit chromatic aberrations and are subject to their overall optical performance while parallax barriers run into diffraction by which image content can leak into the wrong eye. In autostereoscopic systems, crosstalk is the number one complication and often the most difficult problem to combat.

One of the major contributions of crosstalk for lenticular based solutions is the mismatch of pitch between the pixel pitch and the lens pitch which will be discussed thoroughly later in the paper (see section IV).

Crosstalk also exists from the persistence of a display which the image content of one eye's view is still visible in the next frame when that eye is exposed to a new view as shown in Figure 6. To remedy this specific crosstalk, LCD displays with high refresh rates should be used. Additional crosstalk exists due to the blurring of edges of a moving image. Blur occurs in all displays where the luminance of an image is held constant during the entire frame time as shown in Figure 7.

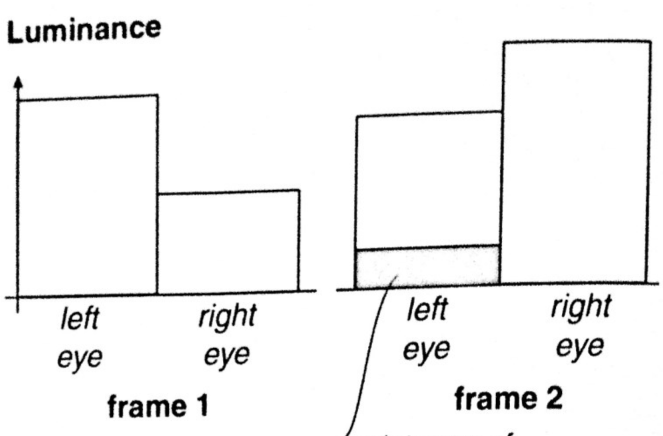

Figure 6 – Crosstalk due to persistence of luminance in an LCD display
[Lueder, 8]

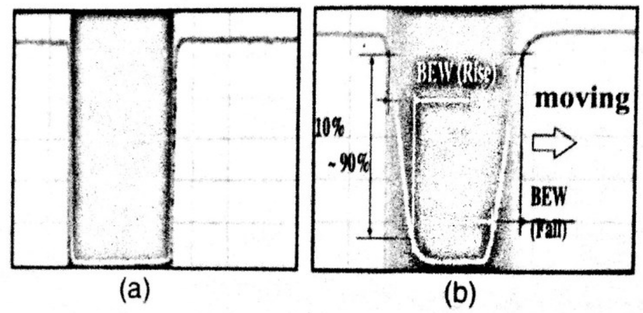

Figure 7 – (a) A stationary image and (b) the blurred edge of a horizontally moving image on an LCD
[Lueder, 8]

In other words, Figure 7 demonstrates the need for a fast decay time in order to eliminate this source of crosstalk. If a black column were to swipe across the display horizontally, the new column of pixels need time to decay and vice versa for the previous column. As a rule for 3D displays, a frame frequency of 240 Hz is used for reducing crosstalk by a factor of four in comparison to a 60 Hz monitor as the addressing circuits in the 240 Hz monitor need to work at four times the speed. This is the primary source of crosstalk for monitors using active shutter glasses for their 3D solution as well as monitors which actively change the position of views relative to the viewer position. In autostereoscopic approaches in which the viewer is only in a single position at a time and every column of will have a static view associated with it, this issue is a very small contribution of crosstalk but the persistent luminance between frames could instead be referred to as "stereo noise." Again, the main contribution of crosstalk in an autostereoscopic approach with lenticular lenses is the pitch offset between the lenticular column width and the pixel pitch width which is discussed thoroughly in section VI below.

C. *Defining Autostereoscopic 3D*

In order to define a 3D display system as being autostereoscopic, the display must give the viewer an impression of a 3D image using the unaided eye (Favalora). To be defined as "automultiscopic", the display is capable of producing many views to the viewer rather than just two usually by means of motion parallax in which the viewer would physically move around the system (or stay in a fixed position and move the system itself) However, automultiscopic displays can and are still referred to as being autostereoscopic, a misconfusion. To give a specific example, polarized glasses that you would wear when going to a 3D movie in theatres is a stereoscopic method (not autostereoscopic) as the display system requires an optical element in front of the eye in order to filter out the polarized light. In addition, people right side of the theatre are viewing the same view as those on the left side. A lenticular monitor is autostereoscopic as given a fixed position a viewer is able to perceive depth. A volumetric display in which you would be able to walk around an image to view different angles of it would be defined as automultiscopic.

D. *Methods for viewing stereo images without glasses (autostereoscopic display systems)*

i. View Interlacing Methods

A large family of autostereoscopic displays use the concept of view interlacing. What typically happens in these types of displays is that there is some image surface (a monitor or front panel display) onto which left eye and right eye views/signals are interlaced vertically (see Figure 8 below). On top of this image surface, there is an optical element which helps "steer" the emitting light coming from the left eye view to the left eye and the right eye view to the right eye. While there are many solutions to achieve this, the most common of these view interleaving displays are displays using a parallax barrier and displays using lenticular lenslets.

1. Parallax Barrier Displays

In 1903 Frederic Eugene Ives invented the concept of parallax barrier after placing black ink on top of a clear plate and determined what happened to an image behind the plate and realized that each eye only saw what the other one could not [5].

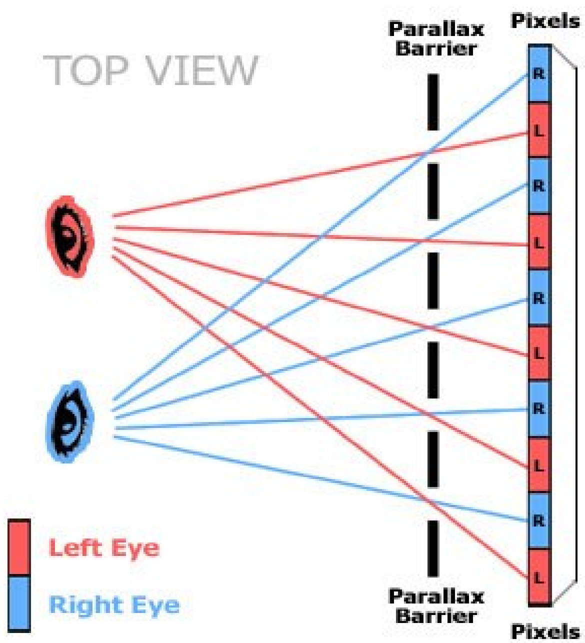

Figure 8 – Simple Demonstration of Parallax Barrier [Aiptek USA]

As seen in Figure 8, there is an image source on the right where the two views meant for each eye are vertically interlaced along the width of the screen behind the parallax barrier. The parallax barrier in front of the screen essentially acts as a microscopic picket fence which could be sometime as simple as a sheet which has very small dark vertical lines on it. At a certain distance away from this display, each vertical line acts as an obstruction so that the left eye would not see the signal meant for the right eye and vice versa. However if the viewer is not on-axis or moves away from the approximal burring point, the images meant for each eye might become switched or burred. The Nintendo 3DS accomplishes its autostereoscopic 3D effect by using a second LCD screen acting as a switchable parallax barrier in front of the one providing light.

2. Lenticular Arrays

a) Basic Principle of Operation

In Figures 9 and 10 we see the basic principles as to how the two methods work in displaying a multiplex image to the viewer properly. In Figure 9 we see an overhead view of Figure 10's lower half (the lenticular lens portion of it). Figure 11 demonstrates that the viewer must be within the acceptable viewing zones in order for the multiplexed image on the screen to be shown to each of the viewer's eyes correctly. When the viewer moves out of the viewing zones the image on the screen will no longer display any degree of depth information correctly. Keep in mind that the viewer can change his or her viewing angle on the Y axis (the axis perpendicular to the ground) but he/she must be within this defined "sweetspot" in terms of the monitor's x-axis and z-axis for the system to work correctly.

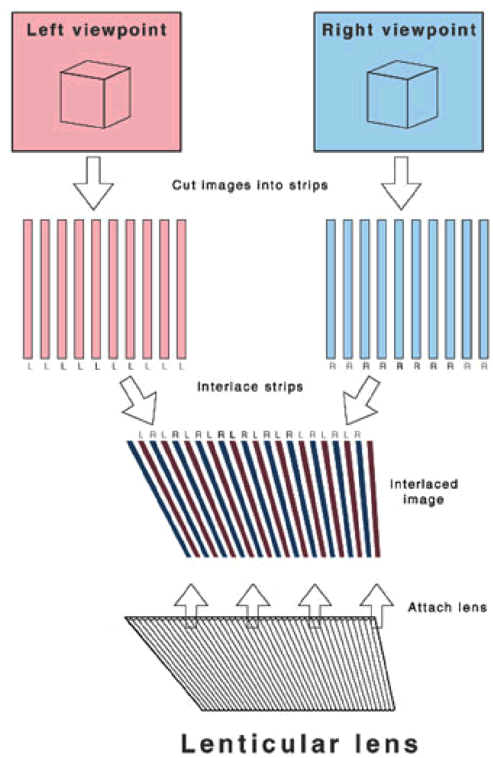

Figure 9 – Viewpoint Interlacing and Lenticular Attachment [Video Technology Magazine]

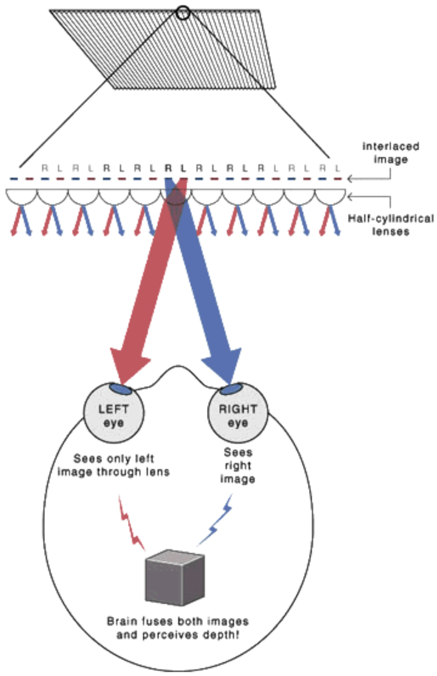

Figure 10 – Simple Model of a Lenticular Autostereoscopic Display
[Video Technology Magazine]

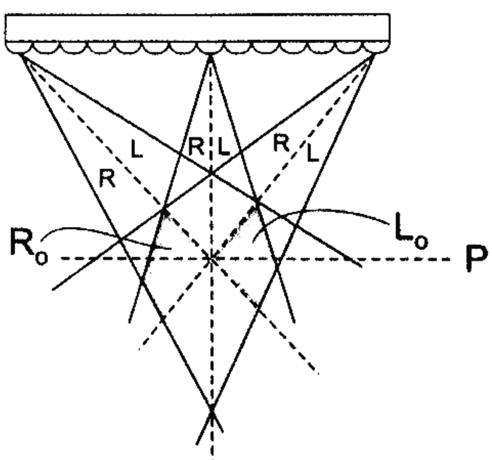

Figure 11 – Images Projected onto the Image Plane (P) & Viewing Zones for the Left and Right Eye Images (Lo and Ro).
[Lueder, 75]

The object, scene, or images are first recorded as a series of two or more dimensional (2D) images taken from a series of two or more horizontally displaced vantage points. We assume "n" equals the number of 2D images taken. For composition of most three-dimensional (3D) images, these images are then interlaced behind the array. "n" pixels are recorded behind each linear convex lens on the lenticular material with each line containing only the image content of a single 2D image. When the viewer sees the final composite image, each eye views only a single 2D image. Due to the fact that each eye receives a different 2D image (the two comprise a stereo-pair), depth is perceived in the scene. For our implementation "n" will be two but the implementation lenticular sheets has the ability to allow for more than two and perceive as though you are moving around the object though means of "motion parallax" (a automultiscopic display).

ii. Other Methods

Other glasses free 3D methods include directional backlight displays and volumetric displays, both of which imply a motion parallax of the viewer (which is not a property of the majority of autostereoscopic systems). To give brief mention on how these solutions work: an example of a directional backlight display is cited as using "guided-wave illumination technique based on light-emitting diodes that produces wide-angle multiview images in colour from a thin planar transparent lightguide. Pixels associated with different views or colours are spatially multiplexed and can be independently addressed and modulated at video rate using an external shutter plane" [10]. Volumetric displays have a larger variety of methods to achieve the illusion of a 3D object as you move around the system. Volumetric displays often use the combination of a high-speed projector or lazer, spinning mirror, holographic diffuser, and a programmable gate array to generate content. Further information on both of these types of technologies can be located within [6].

III. The Lenticular Sheet

Due to the physical structure of the LCD display, if the lenslets' widths are wider than a single pixel (made up of sub-pixels for each channel) then there are going to be issues. This is a large concern with lenticular sheets as they have the potential of not properly aligning with the correct interlaced base image as a result of pitch offset. However by placing a diffuser over the LCD screen before the light hits the lenticular sheet it should be a reasonable solution to avoid the previously mentioned issues. It is important to align the lenslet array to overlap correctly with the front panel display pixels.

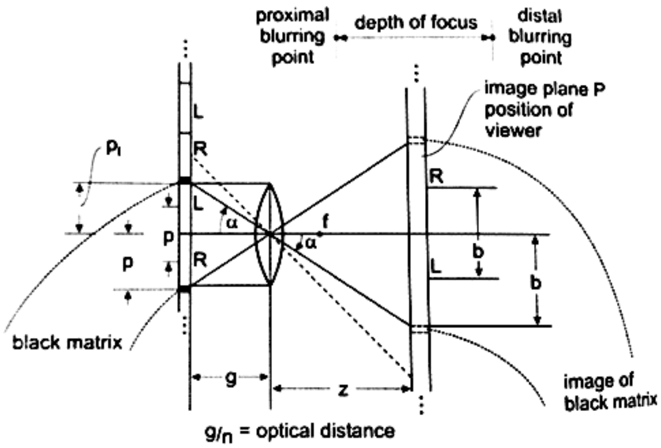

Figure 12 – Optical Properties of a Single Lenticular Element over two Pixels
[Lueder, 76]

In figure 12 we see the projection and magnification of the pixel pitch (p) onto the image pitch (b) (distance between the viewer's eyes) at a set distance away (z). It is possible to determine the characteristics of the system. Each lens in the array has a focal length f, the optical distance, g/n, of the object on-screen with n as the refractive index of that distance g, and the image plane P at a set distance away from the lens, z. b is the intraocular distance, usually 65 mm. On the LCD monitor the pixels are distributed over the length of p. With these variables it is possible to calculate the specifications of the system.

From the lens equation:

$$\frac{1}{(\frac{g}{n})} + \frac{1}{z} = \frac{1}{f} \tag{1}$$

Equation 1 provides:

$$f = \frac{(z * (\frac{g}{n}))}{(z+g)/n} \tag{2}$$

Equation 1 also provides:

$$z = \frac{(f * (\frac{g}{n}))}{(g/n) - f} \tag{3}$$

It is also possible to determine the magnification of each lenticular by:

$$m = \frac{b}{p} = \frac{z}{(\frac{g}{n})} \tag{4}$$

b	interocular distance (65 mm)
f	focal length
g	distance from screen to optical element
m	magnification
n	refractive index
P	image plane
p	width of a pixel
$p1$	pitch of lens array
z	distance from optical element to image plane

Table 1 – Variable Key for Equations

At the edges of a lenticular element, a black matrix is sampled which appears to the viewer as a black mask and can be very disturbing if moving around the monitor. To avoid the lenses projecting the full length of the black matrix into the image plane (P), the lens array pitch (p1) should ideally be slightly smaller than the pitch of the pixels (p).

$$\frac{p1}{p} = \left(\frac{z}{z + (\frac{g}{n})}\right) < 1 \tag{5}$$

From equations 5:

$$z = \frac{p1 * \left(\frac{g}{n}\right)}{(p - p1)} \tag{6}$$

To summarize: From a given interocular distance, b, and from a given pitch of the pixels, p, find the magnification of the system from equation 4; p also yields the lens pitch $p1$ as $p1$ needs to be slightly smaller than p. If the optical distance g/n is known z in equation 6 and f in equation 2 can be determined. In the case where $p = p1$, z becomes infinite, thus the distance that the user must be standing away from the display is very sensitive to changes in both p and $p1$. When designing the system it is important that the specifications of the monitor or screen are accurate in order to determine the optimal pitch of the lenticular so that the image plane P is placed at a reasonable location and the effect of the black matrix is minimized. Unfortunately, due to manufacturing variations from reported specifications as well as inadequate tools to measure these variables, it is often difficult to estimate such unknowns as the optimal distance from optical element to image plane.

If the viewer moves sideward (becomes off-axis from the canter of the display), but remains in the image plane, the perception of the black matrix will become apparent again. For the proposed display to work correctly, the viewer must always be on-axis and at the image plane P which is a distance away z.

IV. Imaging Device versus Lenticular Sheet

When choosing the correct lenticular sheet and monitor to use, it all stems from the number of views you want to place under each lenticular column. In most commercial applications, two views are captured from a scene by use of a 3D camera. In our application, we will only ever have two views and will not be implementing any form of movement parallax in our design. From this relationship we can determine the ideal design of our lenticular sheet (or our monitor) from the below equation:

$$LPI = \frac{DPI}{\#\ of\ Views} \tag{7}$$

Equation 7 – LPI vs. DPI

Often manufactures will specify DPI (dots per inch) as PPI (pixels per inch). A more precise equation taking into account the specifics of the monitor's pixel size and spacing between each pixel (if available and accurate) can be found below:

$$p1 = (views * p) + ((views - 1) * distance\ between\ each\ pixel) \tag{8}$$

Equation 8 – Width of Lenticular Column Calculation

Figure 13 below demonstrates a top-down view of the above situation.

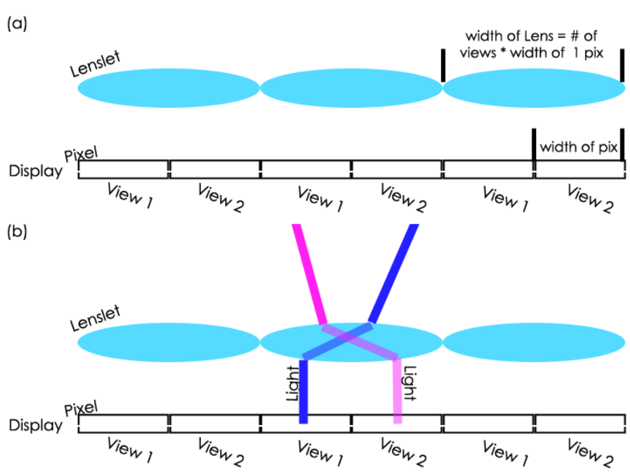

Figure 13 – Two View Lenticular System

Unfortunately, custom engraved lenticular sheets in order to meet this expect relationship between views, pixel width and lenticular width are extremely costly (~$3,000) thus it is important to take into consideration this relationship in order to purchase the correct combination of lenticular sheets and monitor resolution & screen dimensions. Realistically however, this is not an obtainable relationship without a custom engraving. As a result, there is an offset between the previously described relationships which will need to be considered on a radius & frequency basis along the horizontal component of the system. Additional information as to how to process these images with minimizing crosstalk concerns will be discussed in the next two sections.

Special consideration should also be taken into concern with the magnification of the lenticular lenses. Should a magnification be large enough, the lenticular lenses will show a magnified version of the sub-pixels, creating a vertical "rainbow stripped" artifacts all along the monitor (see figure 20 in appendix). To combat this issue, a diffuser should be placed behind the lenticular sheet to ensure the sub-pixels are not sampled by the lenticular lenses. The amount of diffusion should be controlled in an idealised system to ensure the views between pixel columns are not blurred into a single view as well as an overall loss of sharpness. For the constructed monitor, standard tracing paper was used and proved successful.

V. 3D Monitor Construction and Calibration

A properly made interlaced calibration image needs to be created when placing the lenslet array onto the monitor. Assuming at this point the diffuser and lenticular sheet have been cut to match the dimensions of the display, the diffuser (which again is used to prevent the rainbow-colored stripes from occurring once the lenticular sheet is placed on the pixel grid of the LCD monitor) is placed on the monitor followed by the lenticular sheet. It is important that the strips on the lenticular sheet are at a 90 degree angle (vertical) to the absolute best of your ability.

In order to ensure the lenticular sheet is as vertical as possible, a white signal is sent to the LCD display. As the display is placed onto the white screen a moiré magnification effect occurs. In other words, the pixels become magnified and a dim vertical stripe can be seen at the edges of every lenticular column. Using this pattern that forms, the lenticular sheet can be rotated until the pattern on the edges of the lenticular columns are perfectly vertical (see Figure 14 below). Keep in mind, the lenticular sheet needs to be rotated in very fine amounts as just the slightest offset rotation can have degrading effects on the system.

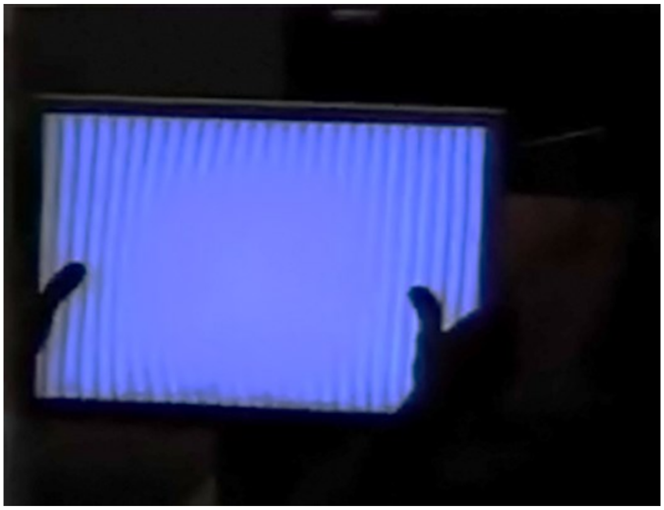

Figure 14 – Placing Lenticular Sheet on White Screen [Hirsch]

In order to account for calibration to ensure the lenticular array is properly cantered over the corresponding pixels, a single white pixel is placed under the canter of every single lenticular. When the correct frequency of lines per unit of measurement is reached, the moiré magnification effect takes affect once again and the monitor should appear perfectly “dull” white when standing on axis at a set distance away from the monitor (see Figure 16, at value 75.6).

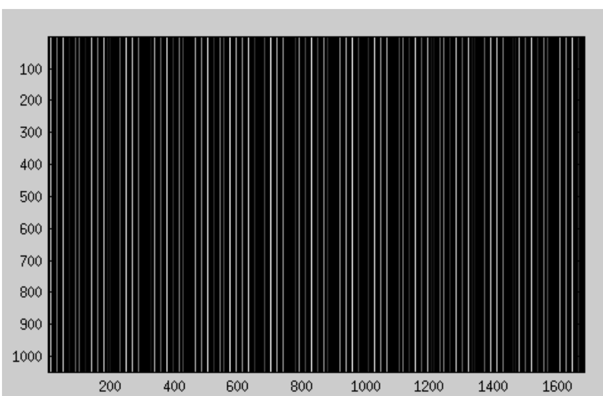

Figure 15 – Example Image of a Calibration Image with a Certain Amount of Lines per Inch for Lens Placement [Hirsch]

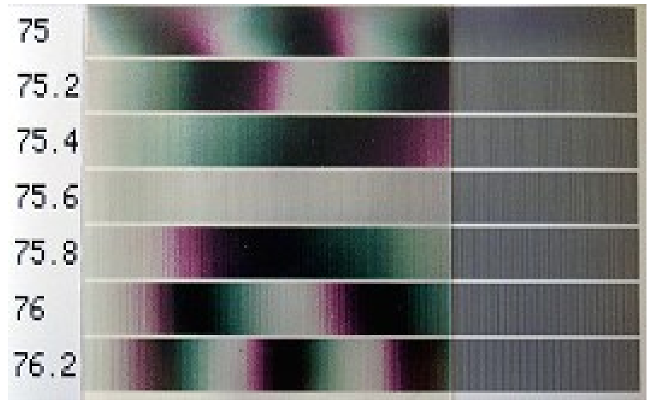

Figure 16 – Lines per Inch Example in which 75.6 is the Ideal Interlacing Amount (as a DPI value) [Hirsch]

However, if you have an even number of pixels under each lenticular, two sub pixels will ideally be under the canter of the lenticular. As a result, in our situation with 2 views under each lenticular, an interlaced pattern of blue and red should be sent to the monitor. When the lenticular is properly aligned with the monitor, a uniform purple color should be viewed on-axis. Any frequency in banding or artifacts viewed once the calibration is complete is a result of the offset between the LPI & DPI which will be addressed in the following section. Keep in mind this horizontal calibration is also extremely sensitive to changes in position and re-calibration will most likely be required if the monitor is moved in any form (this is relative to how the lenticular sheet is mounted onto the front panel display).

VI. Processing Stereo Content with spatial-angular Anti-antialiasing

An interlacing algorithm needs to be developed to account for non-integer ratios between the lenticular size and the pixel size. As a result, the base LCD panel will be offset some the lenslets by some amount. This step involves a certain degree of experimentation unless a very fine caliper tool can be used. In other words, once the lenticular sheet is calibrated in terms of alignment and rotation, the distance between the start first pixel and the start of the first lenticular (on the left wide of the display) needs to be measured depending on the accuracy of the reported specifications of the manufactures.

Once you have that offset, the width of each lenticular column, and the width of each pixel, a process begins in which you find the closest lenticular per pixel. This tells you which spatial coordinate you are to interlace from the light field on a per pixel basis.

VII. Qualitative and Quantitative Assessment of Display

When assessing the quality of a 3D display, regardless of its solution, objective criteria include: "disparity, depth, luminance, contrast, grey shades, and values of the color components such as the location in the chromaticity diagram [or perhaps DeltaE 2000 values between the original content and the displayed content] or the noise level in an image. [The] subjective criteria are harder to define but are subsumed under the perception of structural similarities of the reality of a depth perception" (Lueder, 133). In terms of the human visual system, subjective measurements have a greater degree of correlation to the assessment of 3D displays than do objective measures such as the peak signal to noise ratio. […] Algorithms providing quality information are as a rule based on area-wise or even pixel-wise comparisons between a reference image [or perhaps scene] and the image to be characterized, or between the right eye image and the left eye image, or between two neighbouring areas in an image" (Lueder, 133). The most dominant role in the assessment is the degree of the available extraction of depth from a viewer.

1. *Calculating Crosstalk & Combating It*

Unfortunately, as we are working with a prefabricated lenticular sheet, the construction process involved matching the specifications of the sheet to the monitor to the best of our ability. Regardless of the attempts made, there was a high degree of offset between the pitch of the lenticular width and the pixel width of the monitor. The below equation allows you to calculate a result of this offset how much crosstalk is in the system represented by a percentage. This percentage value represents a system in which 100% crosstalk represents the views completely switched (each eye receiving a different view than it should be). The below equation assumes that the start of the first pixel in the system is aligned perfectly with the first lenticular column.

$$\frac{|L-(P*V)|*\frac{H}{V}}{P*V}=C \tag{9}$$

L	Lenticular Width (typically mm)
P	Pixel Width (aka Pixel Pitch, typically mm)
V	Number of Views Desired Under Each Lenticular
H	Horizontal Pixels (ie. 1920x1080 monitor, H=1920)
C	Percentage of Crosstalk

Table 2 – Variable Key for Equations

The form of the equation $|L-(P*V)|$ allows one to calculate the magnitude offset between the actual pitch relationship and the optimal pitch relationship. $\frac{H}{V}$ determines for how long the extent of this offset is varied along the monitor. Dividing the left side of the equation by $P*V$ enables a percentage to be determined. An example calculation is provided below.

If you had a monitor that had exactly 80 DPI (0.3175 mm pixel pitch) with a 1920x1080 resolution and wanted to have stereo (two views) displayed under each monitor you would purchase a lenticular sheet with 40 LPI (0.635 mm lens pitch). However, due to manufacturer variations in making the sheets, you instead receive a lenticular sheet with 40.03 LPI (0.634492 mm lens pitch). At this point, you have been perfect in your assumptions and assessment in your system and the only variation is due to the variability in the manufacturer's ability to fabricate a precise/consistent lenticular sheet, by the previous equation:

$$\frac{\left(0.000508*\frac{1920}{2}\right)}{(0.3175*2)}=0.768$$

This means that, again, assuming the first lenticular column is aligned perfectly with the first pixel column, that at the last lenticular column it is now covering 0.768 of the two views (pixels) to the right of where it should be and only 23.2% of the views (pixels) it is meant to be over.

However, this is a somewhat idealized case in which there wasn't very much difference between the monitor's pixel pitch and the lenticular pitch. In the actual monitor constructed, the offset between the two was much more as it did not meet the perfect value as a result of a calculation as seen in equation 7.

In calculating the actual extent of crosstalk in the constructed system: the lens pitch was approximated at 0.634492 mm and the pixel pitch was reported at 0.311400 mm, however after extensive calibration and testing, the author of this paper found the pixel pitch was actually closer to a value of 0.311800 mm. Thus the magnitude of offset between the two pitches is at a value of: 0.010892 mm. In addition, the width of the lenticular sheet did not cover the entire extent of the monitor's pixels in the horizontal dimension. As a result, the effective pixels under the lenticular sheet dropped from the monitor's native value of 1920x1080 to 1800x1080.

The resulting calculation of crosstalk in the constructed system is as follows:

$$\frac{\left(0.010892*\frac{1800}{2}\right)}{(0.3118*2)}=15.7197$$

This high percentage of 1571.97% implies of course that the position in which the lenticular sheet is at 100% crosstalk value (when C = 1.0, pixel position H = 114.506), the lenticular sheet is covering the opposite views that was originally under the first lenticular column. In other words, if the original pattern of views behind the first lenticular column was *Right, Left* (to which the viewer would then see *Left, Right* in the left and right eye respectively once the two views pass through the lenticular column), at pixel position 115 in which the crosstalk reaches slightly over 100%, the lenticular column is now covering the views in the order of *Left, Right* and the viewer would then see the *Left* view at the right eye and the *Right* view at the left eye. Without doing anything to combat crosstalk, the views in the system switch approximately 16 times throughout the image, or in other words there are approximately 8 lenticulars throughout the system in which the views are switched and the viewer is viewing the opposite view in each eye that they should be seeing. Keep in mind of course that between intervals of 100% crosstalk, the lenticular column is then covering part of a set views that it should not be.

To combat this, when the value of C hits 0.5 (50%), the previous view is repeated for the first pixel under the next lenticular. To give an example of this 50% crosstalk combating, let's look at the case in which the previous view is then repeated for the first time in the system: At pixel position 57 (H = 57), the crosstalk is approximately under just 50%. Let's assume that pixel 57 holds the *Right* view (again the original interlacing pattern started off as *Right, Left, Right, Left*). Thus in the ideal system, pixel 57 containing the R*ight* view, would be under one half of the 29th lenticular column, and the 58th pixel is under the other half of the lenticular column. However, in the positional case where there is just under 50% crosstalk, the 29th lenticular column is instead covering a sliver of pixel 57 (*Right)*, all of pixel 58 (*Left)*, and most of 59 (*Right)* where again, in an ideal system the lenticular column would not be over pixel 59. As a result of repeating the previous view, pixel 59 then has the previous *Left* view column which was at pixel 58 instead of the intended *Right* view.

As a result of this duplication of the previous view, the crosstalk will then begin to decrease until it reaches a value of -50% in which the process must be repeated. It is best to think of this crosstalk combatant as a sort of "reset" to invert the frequency offset between the two pitches. Of course since you're repeating the previous column, proper consideration must be made to ensure that the final output image will have no geometric distortions in the horizontal dimension (aspect ratio changes). Possible solutions include either "cropping in" which would result in a resolution loss, content aware image resizing to remove seams of the interlaced image to account for the final aspect ratio change as a result of this duplication (however, the energy calculated which is used to generate the seams may consider the edges of every interlaced column to be energy depending on scene content) or showing the *Right* view after the next *Right* on the pixel location after the duplication. The last solution will result in a degraded stereo effect further down the image unless the interlaced image is instead built or interlaced from the center outwards, which would perceptually be ideal.

2. Performing Quantitative Assessments

One of the prominent values to obtain is the value of disparity d and the depth z as a measure for the distance of an object.

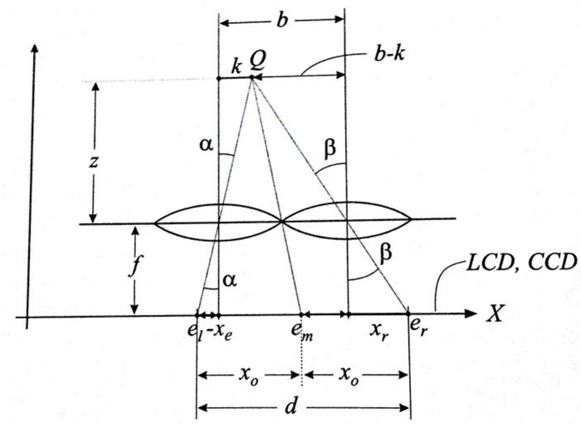

Figure 17 – Relationship between the disparity d and the depth z of a point Q
[Lueder, 134]

Figure 17 above, "when the eye with interocular distance b focus on point Q in the depth z axis, the axis of the right eye is rotated by an angle of $y2$ [from Figure 5] in the opposite direction of $y2$ and hence corresponding to a negative length of the stretch $-x1$on the [FPD in Figure 17]" (Lueder, 134).

$$\frac{-xl}{f} = \frac{k}{z} \tag{10}$$

In which k is the distance between the focus point and the axis of the left lens. It is also possible to obtain

$$\frac{xr}{f} = \frac{b-k}{z} \tag{11}$$

which yields the disparity

$$d = xr - xl = \frac{f * b}{z} \tag{12}$$

The case of two cameras capturing the scene, the distance between the two cameras, also known as the base length, plays a role of the interocular distance b of the eyes. "At x=e_r the center pixels for the right eye image are located while at x=e_l the left eye image are placed. For the LCD […] the distance of e_m is the middle between e_r and e_l […].e_m is exactly the middle as it lies on the straight line from Q to the middle between the lenses with b/2 at each side. The distance from e_m to e_r and e_l is denoted by x_o. Then we get the following equations" (Lueder, 134):

$$e_r = e_m + x_0 \tag{13}$$

from which the following is obtained also:

$$e_r - e_l = 2x_0 = d \tag{14}$$

which provides:

$$x_0 = \frac{1}{2} * \frac{f * b}{z} \tag{15}$$

resulting in:

$$e_r = e_m + \frac{1}{2}\frac{f * b}{z} \tag{16}$$

as well as:

$$e_l = e_m - \frac{1}{2}\frac{f * b}{z} \tag{17}$$

Unfortunately, with only estimations of these variables and no precise way of measuring them, a qualitative analysis would not prove indicative of the actual performance of the display. Should these variables prove to be measureable and the quality data from a given image is retrievable, an algorithm based on the sum of absolute difference is used in order to obtain an sum of absolute intensity differences located in [6] on pages 135-145. In addition, to these uncertainties, as it was mentioned before, this is all relative to the ability to extract information of quality out of a given image shown on the monitor. The process involves a high extent of signal processing and thus is out of the scope of the paper/project. The author feels a qualitative assessment would prove more useful in describing the final system but resources for calculating a quantitative assessment as provided in [6].

3. *Qualitative Assessments*

Due to the high extent of crosstalk as a result of the high offset between the lenticular lens pitch and the monitor's pixel pitch, the perception of depth from stereoscopic images is limited. In addition, there is only a personal preference as to the optimal position of the viewer in terms of distance from the monitor and if he/she should in fact be on-axis when viewing 3D content. It is the author's personal preference to be approximately 53 inches away from the monitor and slightly off-axis to the left in order to increase the perception of depth. Regardless, there is a large degree of crosstalk and the actual depth perception is most likely largely influenced by a psychological factor.

There is a high extent of "ghosting" in which both eyes can view both views/images interlaced for scene content in which the camera had a large base length relative to the objects in the scene. The 3D effect is severely degraded by this offset between the lens pitch and the pixel pitch, signifying that minimizing that offset should be the primary goal when constructing autostereoscopic displays with lenticular based solutions as the resulting crosstalk between the two views can only be reduced to a certain extent.

VIII. Conclusion

Autostereoscopic approaches allow the user to view stereoscopic content without the need for glasses to separate the two views to be presented to each eye. This paper describes a lenticular based solution using a standard LCD monitor and a prefabricated lenticular sheet. Due to the high extent of offset between the pixel pitch and the lens pitch of the lenticular sheet, the resulting system had a large degree of crosstalk and the degree of depth a user was able to extract varied depending on the scene content/images displayed on the system as well as his/her own personal preference to the "sweet spot" (position away from the monitor) as there were no available means to precisely measure the specifications/variables required to measure the optimal distance a viewer should be away from the system.

Future approaches should take into consideration having a lenticular sheet custom fabricated for the system with relation to a precise measurement of the monitor's pixel pitch. Smaller variations between the specifications can minimize crosstalk by the methods discussed in the paper. Special consideration should also be taken into consideration as to the extent of diffusion behind the lenticular sheet as the more diffuse the source behind the optics becomes, the less the views behind each lenticular column can be separated visually.

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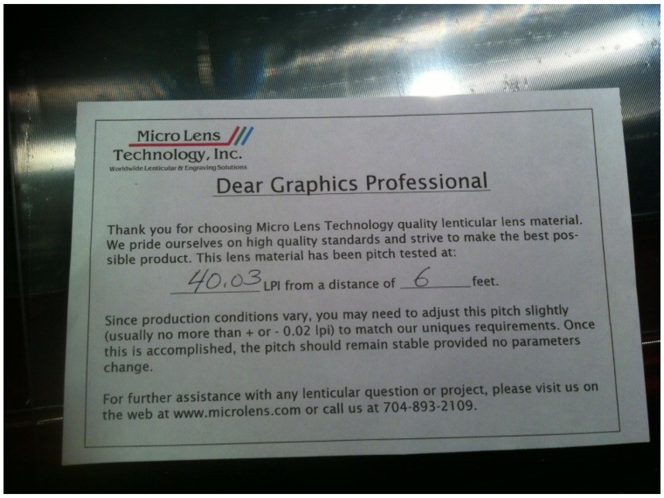
IX. APPENDIX



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Dear Graphics Professional

Thank you for choosing Micro Lens Technology quality lenticular lens material. We pride ourselves on high quality standards and strive to make the best possible product. This lens material has been pitch tested at:

40.03 LPI from a distance of 6 feet.

Since production conditions vary, you may need to adjust this pitch slightly (usually no more than + or - 0.02 lpi) to match our uniques requirements. Once this is accomplished, the pitch should remain stable provided no parameters change.

For further assistance with any lenticular question or project, please visit us on the web at www.microlens.com or call us at 704-893-2109.

Figure 18 – Actual Lenticular Sheet with a LPI of 40.03

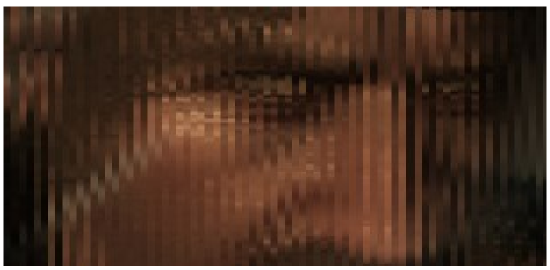

Figure 19 – Magnified & Cropped Interlaced Content

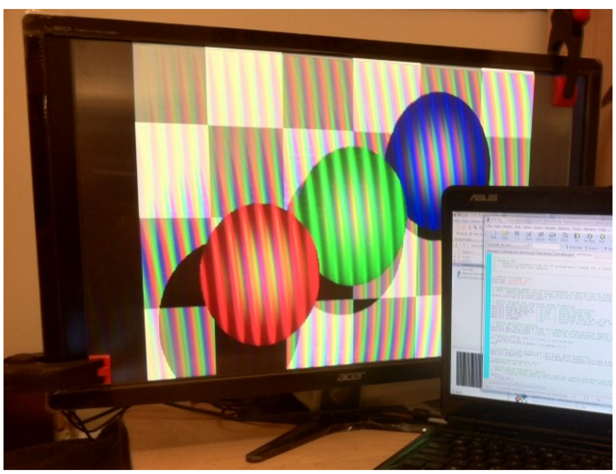

Figure 20 – Monitor without Diffuser behind Lenticular Sheet

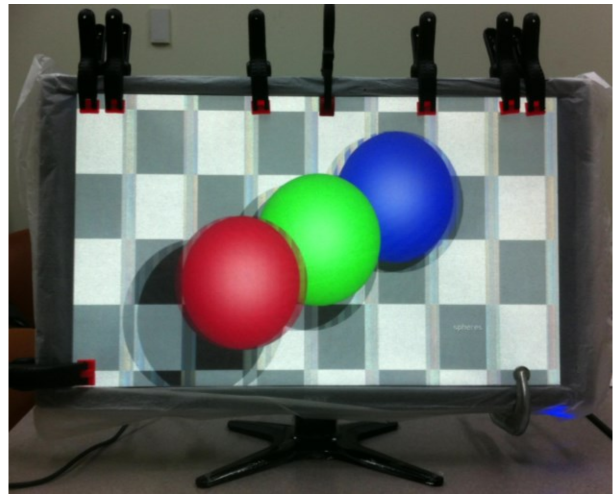

Figure 21 – Final Display (includes Diffuser)