A PROCESS FOR CREATING AUTOSTEREOSCOPIC DISPLAYS OF HISTORIC STEREOGRAPHIC PHOTOGRAPHS

by

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ABSTRACT

During the late nineteenth century, thousands of world events were recorded as stereoscopic photographs or stereographs. Many of these image pairs now reside in museums. Unfortunately, the public rarely gets to see these images due to practical exhibition problems. Current stereoscopic display techniques require special viewing glasses that need to be carefully constructed and maintained.

This thesis identifies the principles involved in creating 3D images that can be viewed without glasses. It also describes a process for the practical implementation of a glasses-free, lenticular method for displaying all of the depth information inherent in stereoscopic photographs. By using morphing software, in-between images are generated between the Left and Right images of the original stereo pair. The resulting sequence of images is then interlaced to produce a three-dimensional lenticular display. The same image sequence can also be used to create an animation which displays the same 3D information.

This process will benefit museums, libraries and other venues interested in publicly displaying autostereoscopic versions of their historic stereoscopic photographs. A complete exhibition might include:

- Internet promotion of the event using animations
- Public display of the large format, high resolution, lenticular displays of the historical stereoscopic photographs
- Gift shop merchandising of smaller copies of the large format versions.
DEDICATION

I want to dedicate this document to Al Razutis, who introduced me to holographic art and to Jeff Poole, who encouraged me to explore stereoscopic photography and computer graphics.
ACKNOWLEDGEMENTS

I want to thank the members of my supervisory committee for their constant encouragement and direction throughout the course of this project. I want to thank Dr. Tom Calvert for showing me an article on autostereoscopic displays at the very beginning of my studies. This opened up a whole new line of thinking which has directly resulted in the production of this report. I want to thank Dr. Steve DiPaola whose understanding of animation and image processing techniques inspired me to pursue my investigations into image morphing. Dr. Dave Fracchia gave me the idea of using historic stereoscopic photographic pairs as a way to test my ideas as well as get involved with other institutions in Vancouver.

I also want to thank Sue Bigelow at the Vancouver City Archives and Kate Russel at the Vancouver Public Library who gave me images to use in my studies. Their thorough knowledge of their collections of stereographs helped to expedite my research.

The combined input from all of these individuals has resulted in a project that will allow the public to appreciate stereographic scenes recorded during Vancouver's early history, without requiring special viewing glasses.
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LIST OF ABBREVIATIONS

dpi  dots per inch

LCD  liquid crystal display

lpi  lenses per inch

ppi  pixels per inch
CHAPTER 1
INTRODUCTION

Throughout the world, archives, museums and libraries have collections of stereoscopic photographs or stereographs that were recorded at the end of the nineteenth century and the beginning of the twentieth century. At that time, viewing stereographs, which fit into specially designed optical viewing devices, was a popular pastime. With the introduction of motion pictures, the public interest in viewing stereoscopic imagery through these devices gradually waned. However, the technology still persists in the form of View-Master reels, 3D movies, anaglyphic comic books and virtual reality LCD shutter displays.

Some sources attribute this decline in popular interest to the necessity to wear special viewing glasses [Lipton, 2002; Spottiswoode, 1955]. Techniques, which do not require glasses for viewing stereoscopic images, have been available in the past, however, high production costs have limited their usefulness. Until recent times, glasses-free autostereoscopic barrier screen and lenticular displays were only economically viable in large print runs.

The continuing development of digital imaging technologies is greatly reducing the costs of producing and viewing stereoscopic imagery. Recently, there has been a rebirth in the production of barrier screen and lenticular images. This has been inexpensively facilitated by an increase in both computer processing speeds and RAM, which are crucial for interlacing the images. The decreasing costs and increasing
resolution of inkjet printers has suddenly made it very affordable to produce customized, one of a kind, autostereoscopic images.

In this context, the central research question for this report is: in light of both the public’s disinterest in wearing glasses to view stereoscopic images and the improving speed and affordability in producing autostereoscopic displays, is there a way to take existing stereoscopic pairs and convert them into lenticular displays? If so, could large collections of historic stereoscopic photographs be put on public display so that current audiences can be made aware of the spatially deep viewing experience which fascinated earlier generations?

This thesis explores the principles involved and provides details for the practical implementation of producing lenticular displays from historic stereoscopic pairs. It describes the underlying principles of depth perception as it pertains to lenticular, autostereoscopic displays, the history of stereoscopic photography and displays, as well as a process for turning conventional stereoscopic photographic pairs into autostereoscopic lenticular displays. This process includes image processing, creating in-between images through morphing techniques, interlacing the in-between image sequence and finally printing and laminating. The flowchart in Figure 1 sets out this process.
Figure 1. Flowchart of procedures for creating animations and lenticular prints from stereoscopic photographs.
CHAPTER 2

PRINCIPLES OF DEPTH PERCEPTION

This chapter identifies some of the factors which help us to determine the depth positions of objects within a scene. This summary is not exhaustive - rather, it focuses on the factors that will have a direct bearing on producing high quality lenticular images. Certain aspects actually allow some leeway in the fidelity of the reproduction of the spatial scene, due to the forgiving qualities of the human perceptual system.

The first section explores monocular depth cues, or depth cues which can be learned by individuals without binocular vision. Further sections go on to describe binocular vision or stereopsis. Finally, this chapter also looks at some of the anomalies of binocular vision.

**Learned Monocular Depth Cues**

Even a person who has only one eye can determine the spatial relationships within a scene through learning. These basic cues, which also augment binocular vision, are occlusion, linear perspective, texture gradient, image size, aerial or atmospheric perspective, shading and motion parallax. These factors will help give the final lenticular scene “more depth” than can be provided by the short focusing properties of a lenticular lens array alone.

**Occlusion**

If one object obstructs the view of another object, then it is perceived as being closer [Valyus, 1966, p. 57]. Figure 2 is a simple example of how closer objects screen the view of farther objects.
Figure 2. Depth Determination by Arrangement of Objects. The tree is closer than the house because it occludes part of the house.

This perception can be challenged, however, by binocular pseudoscopic images, which will be discussed later. We will also see that occlusion becomes a major consideration during the morphing process.

**Linear Perspective**

Objects that form parallel lines or edges, which converge to a distant vanishing point, are perceived as being the same size even though their image size becomes smaller [Steinman, 2000, p. 178]. Figure 3 uses a simple row of trees as an illustration.

Figure 3. Linear Perspective and Vanishing Point.
**Texture Gradient**

Associated with linear perspective is the phenomenon of texture gradient changes, whereby distant objects are not only smaller, but also more densely packed than closer objects [Steinman, 2000, p. 178]. A checkerboard is used to demonstrate this point in Figure 4. Even though the foreground squares are physically larger than the background square, they are all perceived as being the same size.

![Figure 4. Changes in Texture Gradient](image)

**Image Size**

In most photographed scenes, numerous clues to distance are usually present. We make judgments of distance only after our visual system considers all of the available information. For example, in Figure 5A, the two trees could be perceived as being different sizes. However, as in Figure 5B, if the distance of the smaller tree is perceived as being greater than the larger tree, then both trees are perceived as being the same size [Steinman, 2000, p. 176].

![Figure 5. Image Size and Other Depth Cues](image)
Aerial Perspective

Distant objects also appear less sharp and with lower contrast than closer objects due to the light scattering, atmospheric effects of moisture and air pollution. [Valyus, 1966, p. 65] Figure 6 is a simple drawing of trees that conveys this concept.

Figure 6. Atmospheric or Aerial Depth Cues

As will be discussed later, this is useful information when determining the zero point plane of the lenticular image. Objects of a scene which are further away from the zero plane will be naturally blurred by the low focal length of the lenticular sheet. Further blurring also occurs when low resolution printers are used. These “defects” can actually be interpreted by viewers as atmospheric effects, rather than to poor image fidelity.
Shading

The direction of lighting and the shading of an object can indicate an object's depth. Figure 7 uses shading to illustrate concave and convex hemispheres [Steinman, 2000, p. 180]. This is particularly true when objects lack shape-defining textures.

Figure 7. Concave and Convex Shading

Motion Parallax

As our head or body moves, motion parallax can provide us with clues as to the three dimensional arrangement of objects. In Figure 8, the camera (or eye) is fixated on the sphere [Steinman, 2000, p. 181]. As the eye moves from side to side, the images of the square bar and the tetrahedron shift their positions relative to the sphere. The relative distances of the objects from the fixation point can be judged by the velocity of the motion.
As Steinman [2000] points out,

Motion parallax helps animals with limited binocular visual fields to see depth. An example is the head-bobbing movements of pigeons. However, motion is still useful as a depth cue in species with well-developed stereopsis. Depth judgments based on motion parallax are almost as accurate as those based on binocular disparity; that is, motion parallax thresholds are nearly as accurate as binocular stereo acuity.
thresholds. This is not surprising because motion parallax produces image displacements on the retina that are equivalent to those produced by disparity. [p. 180]

It will be shown later that after morphing between the Left and Right images of a stereoscopic pair, the image sequence can be converted into a movie file or a GIF animation. The resulting movie of the disparity between the Left and Right views, looks as if it was filmed by a panning camera. All of the spatial relationships between the objects in the scene can be inferred from this movie.

**Innate Binocular Mechanisms**

The depth cues mentioned above are learned over time. No one is inherently born with knowledge of these depth cues. However, stereopsis, the integration of the images from two human eyes in the visual cortex, gives us a truly innate capability to determine depth. As Steinman [2000] states, “Stereopsis is thought to be our sole robust binocular cue to depth” [p. 185].

**Stereopsis or Binocular Disparity**

Most people have two functional eyes. To fully understand what version of the world each one of our eyes sees, try this simple experiment. Hold one of your thumbs in front of your face and at arm’s length. Close your left eye while keeping the right eye open. Look at the objects that are visible behind your thumb. Next, without moving your hand, close your right eye and open your left eye. Notice how your thumb seems to have jumped into a new position relative to the background objects. This is because each one of our eyes sees a slightly different view of the world. When both of our eyes are open, it is the brain that takes these two disparate images and combines them together to give us a sense of depth. [Lipton, 1993]
The major advantage of a binocular vision system over a monocular system is that we are much more accurate at perceiving depth when we use two eyes than when we use only one eye. This is because with two eyes we can achieve stereopsis. Stereopsis greatly enhances our ability to judge depth. It allows us to be much better at figure-ground segregation (e.g., picking out camouflaged objects from their surrounds), avoiding collisions with looming objects, and accurately navigating through our environment than we would be with one eye alone.

Stereopsis is the combining of information from both eyes to achieve a three-dimensional percept of the world. Whereas monocular cues to depth are inferences that the visual system has to make, stereopsis is the visual system’s only direct means for seeing depth, and it is mediated by special mechanisms built into the visual system. [Steinman, 2000, p. 185]

When this observation was combined with photography in the early nineteenth century, stereoscopic photography was born.

**Convergence and Accommodation**

There are two other innate biological means for determining depth. They are accommodation and convergence of the eyes. The eyes rotate inwards or converge when an observer looks at objects which are very close. When the eyes, unnaturally rotate away from each other, wall-eyed vision occurs. Wall-eye vision only happens when stereo images are not correctly registered. Looking at images which cause wall-eye can produce eye strain and subsequent headache. [McAlister, 1993, p. 2]

Accommodation is the change in focal length of the lens of the eye as it focuses on specific regions of a 3D scene. The lens changes thickness due to a change in tension from the ciliary muscle. This depth cue is normally used by the visual system in tandem with convergence. [McAlister, 1993, p. 2]

However, Steinman [2000] states that “the visual system is able to use the neural signal for convergence as sole indicator of distance only to a limited extent” [p. 184]. There is still some debate as to the importance of these two phenomenon in helping with
depth perception. From the standpoint of lenticular imaging, they are not significant due to the viewing distance to the display and the shallow depth of field of the lenticular picture.

**Stereo Acuity**

Stereo acuity is defined as the smallest depth difference we can perceive (depth discrimination threshold). Humans are capable of detecting a shift of one eye’s image (binocular disparity) as small as $1.25 \times 10^{-3}$ degrees. [Steinman, 2000, p. 193] The upper limit of stereoscopic disparity is a separation of about 1.67 degrees. At this separation between analogous points, the visual system has difficulty assessing depth. [McAlister, 1993, p. 15]

Stereoacuity depends on the interpupillary distance. The greater the distance between the two eyes, the larger the disparity and the greater the depth effect. The normal interpupillary distance is 65mm. This is usually the distance between the two lenses of a dedicated stereo camera. The distance between the lenses will replicate the scene as naturally as possible from a human perspective.

The distance from the camera to the point of interest is also important. Disparity is inversely proportional to the square of the viewing distance. As the viewing distance changes from 1 meter to 100 meters, the disparity will change by a factor of 10,000. This means that the same object displacement needed to see a depth difference at 1 meter must be increased 10,000 times to be seen at 100 meters. Our binocular vision is much more accurate at using disparity at close distances than at long distances. For an average interpupillary distance of 65mm, the geometric limit for disparity occurs at a fixation distance of about 1,320 meters. Objects beyond this limit all appear to be at the same distance. [Steinman, 2000, p. 197]
Knowing this last piece of information will help with choosing the best historical photographs to convert into lenticulars. Photographs with lots of close, foreground objects will give the greatest sense of depth. Stereo photographs of mountains and other distant landscapes are often poor subjects for this process.

Another factor, which also affects stereo acuity, is luminance. The dimmer the scene’s luminance, the less our sensitivity to depth. [Steinman, 2000, p. 198] It is also difficult to see stereopsis at very low contrast. Increasing the stimulus contrast even a little will greatly improve depth perception. Conversely, if the two eyes receive images of unequal contrast, stereo acuity will be degraded considerably. [Steinman, 2000, p. 199]

The above point must be taken into consideration during both the pre-morph and post-morph processing of the lenticular image sequence. Historical photographs with poor contrast or significant blurring must be enhanced through colour correction and sharpening. If these techniques cannot appreciably improve the contrast of the original stereo pair, the stereograph will prove to be a poor candidate for converting into a lenticular display.

The colour of objects also affects binocular perception. Blue is more difficult to assess than red or green. This may be explained by both the lower resolution and lower contrast sensitivity of the eye’s blue cone system. [Steinman, 2000, p. 198]

Another stereo acuity factor involves the length of time we are allowed to view a stereo picture. We are much more sensitive to depth if we are allowed to view the picture for at least 1 second. Fine disparities take longer to detect than coarse disparities. Random-dot stereographs take longer to process than simpler line stereographs. [Steinman, 2000, p. 198]
**Binocular Confusion**

In the first section of this chapter we explored the various depth cues that can be successfully processed by only one eye. In the second section, we learned how stereoscopic depth perception requires two eyes. We will now examine what happens when the brain has to analyze two radically different monocular images presented independently to each eye.

**Suppression**

What if each eye were to see a completely different image? Steinman [2000. p. 122] suggests that one way the visual system handles conflicting information is to simply “ignore” or “turn off” either all or part of the image to one eye, so that only one of the two different images reaches conscious perception. This suppression may not occur instantly; it may take up to 75 to 150 ms to begin. Steinman illustrates this concept by describing a simple test (Figure 9):

A horizontal line is presented to the left eye and two closely spaced vertical lines to the right eye. When these two monocular images are superimposed, part of one eye’s view disappears. In this example, a portion of the left eye’s line (between the two vertical lines) disappears in the binocular percept. This corresponds to a local suppression of the left eye’s information. If we close the right eye, that part of the left eye’s image reappears. The suppression only occurs under binocular conditions. [Steinman, 2000, p. 124]
If the two eyes are equal in their contribution to the binocular visual system (where one eye is not very dominant over the other), the eye presented with a weaker image will be suppressed. An image that is dimmer, of lower contrast, blurred, stationary, or in the retinal periphery will be more likely suppressed. [Steinman, 2000, p. 125]

We will later see that this may be a benefit when morphing processes, described in Chapter 4, fail to fully deal with occluded objects. If the affected area is small enough in detail, the visual system of the viewer may not notice the ambiguous region in the finished lenticular.

**Binocular Rivalry and Luster**

This is an intermittent and alternating suppression of brightness, colour and/or contour of one, then the other, eye. Binocular rivalry usually occurs with vastly dissimilar images in each eye. The vastly differing luminances of the images are not simply fused.
Instead, the background appears glossy, silvery or shimmering like polished chrome as in Figure 10. [Steinman, 2000, p. 133]

Figure 10. Binocular Luster.

Stereoscopic depth can be affected by a scene containing lustrous imagery. Figure 11 illustrates that depth perception can deteriorate when lustrous images are surrounded by areas of vastly differing tonalities. [Valyus, 1966, p. 54]

Figure 11. Lustrous Depth Perception in Different Environments
The main point is that in order to avoid unintentional shimmering, both images of the original stereo pair must have similar luminances. However, this may not always be the case with older, archival photographs. Sometimes the shutters of the dual lens cameras worked at different speeds, therefore one image is brighter or darker than the other image. Sometimes poor storage has resulted in luminance differences. In any case, colour correction will be required to bring both images to the same brightness levels before morphing and interlacing.

**Miscellaneous Notes on Stereoscopic Depth Perception**

**Binocular Vision and the General Population**

From a public exhibition standpoint the following piece of information should always be kept in mind:

It is generally accepted that between 10 and 15% of the human population do not use stereoscopic vision (although they can identify relief using other means than binocular vision). There are different reasons for this such as, for example, lack of sight in one eye. Up to 30% of the population have some difficulty seeing stereoscopically. [Ninio, 2000]

It will be shown that one way around this problem is to exhibit an animation of the morphed image sequence along with the lenticular image.
Flatness of Stereoscopic Pairs

One comment about viewing stereo pairs through a stereoscope is that the scene appears as if it is made out of card board cut-outs arranged in depth. The effect, known as “card boarding” is a limitation of the recording camera’s two vantage points of the original scene [Steinman, 2000, p. 206]. Figure 12 illustrates this point with stereo images of a downtown Vancouver street scene, circa 1900.

![Cardboard Effect of Stereo Pair](image)

Figure 12. Cardboard Effect of Stereo Pair. *Note.* Stereoscopic photograph courtesy of the Vancouver City Archives.

Carefully morphed lenticular displays overcome this problem by presenting more than just the two original views. This causes the perceived scene to have a more natural, rounded look.
Pseudoscopic Imagery

If the images of a stereoscopic pair are reversed, in other words, the Left image is viewed by the right eye and vice versa; the entire scene is turned inside out. Confusion develops because the monocular cues of occlusion conflict with the binocular perception of far objects being closer than near objects. Figure 13A shows a normally arranged pair and Figure 13B shows the pseudoscopic result when the pair order is reversed.

Figure 13A. Typical Orthoscopic Stereoscopic Pair Arrangement

Figure 13B. Pseudoscopically Arranged Stereoscopic Pair
Since lenticular interlacing software requires that the image sequence is loaded in a particular order (usually with the Left image first and the Right image last), it is imperative to make sure that the Left image is indeed the Left image. Some collections contain digitally archived stereoscopic images that have been naively scanned in backwards. Therefore, it is imperative to verify the stereo pair’s orientation at the very beginning of any image processing procedure.
CHAPTER 3
STEREOSCOPIC PHOTOGRAPHY AND DISPLAYS

Early Stereoscopic Photography

The best quote that summarizes the initial explosive popular growth in viewing stereoscopic images is provided by Waldsmith [1991]:

From the early 1850's to the late 1930's, millions of stereoscopic photographs (stereographs or stereo views) were made by commercial and amateur photographers. At the height of their popularity in the late 1890's a stereoscope and a selection of views could be found in nearly every middle- and upper-income home in the United States....The development of the stereoscope must have been a visual revelation to the Victorian gentry of the 1850's, and it is understandable how stereoscopes became a parlor entertainment craze. [p. 1]

This explains the large number of stereoscopic images that are in collections throughout the world. However, in order to reconstruct these early images in a lenticular format, it will be necessary to know a bit about the original cameras that recorded the early scenes.

Of particular importance, is the separation between the two camera lenses that recorded the original stereo pair (assuming that a two lens camera was used and not a single camera shifted from one position to another between exposures). As we will see later, this lens separation number is important to know during the interlacing process needed to make the final lenticular picture.

Ideally, the type of camera used to make the original stereo pair is documented in archival notes. There is some published literature that lists the specifications of these early cameras, such as the separation distance between the lenses. If the specifications
cannot be found, or the type of camera is unknown, a general rule can be applied to calculate the distance. Generally speaking, cameras with fixed lenses had a separation distance ranging anywhere from 62mm to 70mm because the average human interocular distance (distance between each eye) is 65mm. [McKay, 1953, p. 27]

**Stereoscopic Print Displays Requiring Glasses**

After a stereo photographic pair has been recorded, there are a variety of ways to view the final images so that the original scene’s depth is visually reconstructed. These print display methods are divided into two groups: displays that require the wearing of special glasses and autostereoscopic, glasses-free displays.

**Stereoscopes**

This is the oldest form of displaying stereoscopic photographic pairs. Initially they were viewed using the cumbersome Brewster stereoscope, however Oliver Wendell Holmes and Joseph Bates dramatically improved the device in 1860. Their innovation resulted in an explosive popular interest in viewing stereographs. The Golden Age of stereoscopic photography lasted from 1851 until approximately 1900. At one point, almost every Victorian period household had a stereoscope. However, its popularity went into decline at about the same time as the invention of motion pictures [Waldsmith, 1991, p. 2-4]. Figure 14 shows the author of this thesis using a Holmes-Bates stereoscope to view a stereograph (a card containing a stereo pair).
A modern version of the Holmes' stereoscope was manufactured by View-Master, which also published reels containing stereo pair transparencies.

This method still reconstructs the highest quality images with the greatest sense of depth. The only drawback, besides requiring glasses, is that the three-dimensional scenes appear to be comprised of multiple flat layers arranged in depth. As pointed out in Chapter 2, this effect is called "card boarding". As will be mentioned later in this section, lenticular displays overcome this problem by displaying multiple views of the scene at the same time.

**Anaglyphs**

Invented in 1858 by Joseph Charles d'Almeida [Pellerin, 2000], anaglyphs are made by colourizing the Left image red and the Right image blue. The person viewing the printed anaglyph must wear special glasses with a red filter covering the left eye and a blue filter covering the right eye. If the printing inks have been correctly matched to
the light transmission properties of the filters, the left eye sees only the Left image and the right eye sees only the Right image.

This technique was widely used in the 1950’s to view 3-D movies. It is still used in some comic books and the occasional magazine. Figure 15 shows the author reading an anaglyphic comic book.

Figure 15. Red and blue glasses are used to view anaglyphic comic books.

Unlike the original full colour stereo pairs used to generate the anaglyph, the final image is essentially a duotone. Many people report eye fatigue, and in some cases nausea, when viewing anaglyphs [Love, 1993, p. 27]. It can also take several minutes for the brain to adjust to and synthesize the differently coloured images. Another drawback is that, over time, the inks will have a tendency to fade. The faded images no longer reflect the same wavelengths of light as the filters on the glasses. This can result in “cross talk” or “ghosting” whereby one eye sees the image meant to be viewed only by the other eye. This can significantly degenerate the perception of depth.
**Vectographs**

Invented in 1936 by Edwin Land of the Polaroid Corporation [Reynaud, F., Tambrun, C., & Timby, K., 2000, p. 167], depth is perceived by using glasses with polarizing filters. The process involves printing the stereo pair with special iodine-based inks onto two sheets of polyvinyl alcohol, which are cross-polarized. The Right image is drawn on one sheet and the Left image is drawn on the other sheet. The two sheets are registered and laminated together. Wearing correctly polarized glasses ensures that each eye sees only the image meant for the appropriate eye. [Love, 1993, pp. 28-30]

**Glasses-free Displays**

**Free-Viewing**

The cheapest form of viewing stereograms without glasses is called free-viewing. Essentially the viewer looks at the stereo pair either by focusing at infinity or, if the Left and Right images have been reversed, by crossing their eyes. This technique is not popular because it takes time to master and/or it can be physically uncomfortable [Ferwerda, 1990, p. 32-39].

**Parallax Barrier Screen**

Developed in 1903 by Fredrick Ives in the United States and in 1906 by Eugène Estanave in France, this display technique requires that the Left and Right images be divided up into alternately interlaced, thin, vertical slices. A barrier screen, consisting of alternating dark and clear stripes, with the same frequency (or pitch) as the interlaced image, is placed a short distance in front of the interlaced print. When both the print and the screen are properly aligned and the viewer is standing in the correct viewing...
position, the left eye of the viewer sees the compiled Left image, while the barrier screen prevents it from seeing the image meant for the right eye. The inverse is true for the right eye. The viewed result is a scene complete with all of the original depth information. Figure 16 diagrammatically illustrates the components of a barrier screen display.

Figure 16. Top View Schematic of a Barrier Screen Viewing System.

A drawback of the two-view barrier screen display is its narrow viewing zone. If the viewer moves outside of the optimal viewing zone, they experience a switching of the left eye and right eye views. The result is a pseudoscopic image. This problem is solved by adding multiple views between the original Left and Right views. This adds a "look around" capability, where the picture moves through a sequence of views as the viewer moves from side to side, revealing different aspects of the recorded scene [Love, 1993, p. 31]. This also alleviates the "card boarding" effect of stereo pairs.
Limitations of the Parallax Barrier Screen System

The major limitation of the parallax barrier screen system is that the overall brightness of the image is reduced because the opaque barrier screen takes up at least 50% of the image’s surface. [Valyus, 1966, p. 140] Another problem is that, if the barrier screen is fine enough, diffraction effects cause the resulting image to be blurred. [Valyus, 1966, p. 141] Viewers also have to stand in a very specific spot in order to appreciate the three-dimensional image. This prevents a large group of people from viewing the same image at the same time.

This type of display has given way to the much brighter lenticular screens which are described next.

Lenticular Screen

In 1908, Gabriel Lippman proposed the idea of integral photography, which uses an array of spherical lenses to record and later reconstruct a scene in full depth.

Lippmann’s special plate would be made up of lenticular spherules on one side, each one acting as a lens, and corresponding convex surfaces on the other side bearing the light-sensitive emulsion. By photographing onto this plate, without placing it in a camera (‘each cellular system functions as a camera’), one gets as many images as lenses. After inversion from negative to positive, direct observation of the backlit plate makes a single image appear, ‘because of the inversion of the rays of light. [Frizot, 2000, p. 171]

Lippmann’s technique was fraught with technical difficulties: primarily the exact realignment of the developed print with the lenses. In 1937, Maurice Bonnet, working in Paris, developed a practical method to realize this process using a sheet of fine
cylindrical lenses. Roberts [2003] describes the principles behind recording and reconstructing lenticular displays:

A lenticular lens sheet consists of a linear array of thick plano-convex cylindrical lenses, known individually as "lenticules". The lens sheet is transparent and the rear face, which constitutes the focal plane, is flat. A big advantage was it was optically analogous to the parallax barrier screen.

These principles hold true if, instead of directly recording the original scene onto the back of the lenticular sheet, a lenticular image is printed onto paper which is then adhered to the back of the lenticular sheet. Figure 17 is a magnified drawing of a lenticular screen and its registered image.

![Lenticular Sheet](image)

Print with interlaced Left and Right images

Figure 17. Components of a Lenticular Display

More than two images can be placed behind each lenticule. As with barrier screens, sequential views prevent the sensation of "card boarding" by making the objects in the scene appear more rounded. Figure 18 shows the top view of a cross-
section of a lenticular sheet with 4 images interlaced behind it. The focal properties of
the lenticules insure that each eye sees the appropriate slice of the scene as the head
moves from left to right. [Bourke, 1999]

Figure 18. Top view of a lenticular print with multiple interlaced images.

Roberts [2003] points out that although lenticular displays are optically identical
to barrier screens, they are significantly brighter. When Valyus [1966, p. 147] compared
the brightness values between barrier and lenticular screens he found that lenticular
screen images can be up to 45 times brighter than their barrier screen equivalents. It is
for this reason that lenticular screens are used for prints whereas barrier screens are
used only with back-lit images.

Bonnet also realized, that instead of a sequence of static views, he could display
an animated sequence behind the lenticular screen. As the viewer moved their head,
they would see a short animated movie. [Frizot, 2000] Personal computers can now
play back these image sequences, as either short movie clips or as animated GIF's,
without the need for the lenticular screen.
Today, plastic lenticular sheets with varying numbers of cylindrical lenses per centimeter (pitch) and with adhesive backings are readily available. Earlier mechanical devices, which were used for interpolating the images, have been replaced with affordable and more flexible software applications. All of these images can now be conveniently printed on most desktop inkjet printers.

Overview of Barrier Screen and Lenticular Sheet Displays

As Love [1993] points out, "Parallax barrier displays present very high-quality images. The main drawback is that since so much light is blocked by the barrier, the image is often dim, and it is only practical to display backlit transparencies such as Cibachrome display transparency film." [pp. 31-32]

Love [1993] then goes on to compare and contrast the two types of displays:

Barrier displays are often considered superior to lenticular ones, but the quality of a lenticular display depends on the uniformity and quality of the lenses. Large, high quality lens sheets can be produced, though this is a difficult task, especially in quantity, and the sheets are subject to shrinkage during fabrication. They can also be improved through the use of elliptical rather than cylindrical lenses. Lenticular displays do offer at least one significant advantage over barrier methods. Since they use refraction rather than occlusion, image brightness is superior. Lenticular displays have no special lighting requirements, making them more portable and useful with images recorded on any medium, not just transparencies. This fact, combined with the ability to fabricate lens sheets inexpensively from plastic, accounts for the popularity of lenticular over barrier strip displays. [p. 32]
CHAPTER 4
PRINCIPLES OF MORPHING

Introduction

In the past, lenticular images were made with multi-lens cameras, sometimes having as many as twelve lenses on the same camera. However, early stereo cameras, prior to the 1930's, only had two lenses. The question is: can a sequence of views be created between the Left and Right images in order to mimic the effects of a multi-view camera?

Morphing techniques, which are widely used by visual effects artists to gradually metamorphose one image into another, involve the sequential warping and cross dissolving of one image (the "source") into the shape of another image (the "target"). As the morph sequence progresses, the initial frames look like the source image, the middle frame is an average of the source and target images, and finally, the last frames look more and more like the target image.

Zhang [2001] describes how morphing techniques have developed:

Before the development of morphing, image transitions were generally achieved through the use of cross-dissolves, e.g., linear interpolation to fade from one image to another. The result is poor because without real warping, the double-exposure effect will be apparent in misaligned regions. Warping must be used in order to achieve a fluid transformation and since the cross-dissolving is very simple, warping becomes the major problem of morphing techniques.

Warping techniques can be classified into two groups: landmark-based and feature-based [Zhang, 2001]. The first technique requires the manual placement of pairs...
of points or line segments (land-marks) on corresponding parts of the source and target images. Feature-based techniques use identifiable features, such as pixel intensities, to control the warping. It will be shown that feature-based warping techniques pose a much more difficult problem to solve than landmark-based techniques.

**Land-mark Morphing**

Pairs of marker points or lines are manually placed on the source and target images. The morphing program then uses these markers to calculate how the source image will be warped and dissolved to match the shape of the target image. Both methods can quickly produce good morphing effects.

**Point Morphing**

Software packages, such as the CHV Morph plug-in for Apple Computer’s Final Cut Pro, place one mesh over the source image and another mesh over the target image. Vertices on the source image’s mesh are positioned over features that are to be morphed into features on the target image. The corresponding vertices on the target’s mesh are moved to the destination features on the target image. Figure 19 shows a screen shot of CHV Electronic’s mesh morphing effect.

Figure 19. Point morphing meshes on source and target images. *Note.* Photographs courtesy of Christoph Vonrhein, CHV Electronics, [http://www.chv-plugins.com](http://www.chv-plugins.com).
Since not every pixel is specified, an interpolating function is used to control the surrounding pixels. These surrounding pixels will move somewhat less than the control point, with the amount of movement specified by a weighting function [Claypool, 1997].

Although this technique works very well, it cannot deal with pixels that need to fold over other pixels in order to reach their target destination. Therefore, it is incapable of solving problems of occlusion and has limited use for dealing with complex and scenically deep, stereoscopic images.

Another drawback is the inability to import vector lines created in other software applications. There are numerous algorithms that can trace bitmap images with vector lines. However, these lines and points can not be meaningfully imported and used to automate at least part of this morphing process.

**Line Morphing**

A more satisfactory method for solving the problem of occluded features, which are regular aspects of stereoscopic photographs, is line morphing. Software applications such as Avid Technology’s “Elastic Reality” can easily handle morphing by means of corresponding pairs of lines. A pair of corresponding lines in the source and target images are used to define the pixel mapping between the two images. Once again, Zhang [2001] best describes this method:

In addition to the straightforward correspondence provided for all points along the lines, the mapping of points in their vicinity can be determined by their distance from the line. Since multiple line pairs are usually given, the displacement of a point in the source image is actually a weighted sum of the mappings due to each line pair, with the weights attributed to distance and line length.
The influence of the different lines can be adjusted by modifying a weighting factor. This technique is more expressive than the mesh warping technique. Another advantage is that vector line tracings of bitmap images can be imported and used to automate some of the process. Line morphing procedures are described in considerable detail in the next chapter.

**Feature Morphing**

One of the most time consuming tasks in point or line morphing is manually setting the points or lines in the source and target images so that the metamorphosis is smooth and natural. An algorithm to automatically select the morphing markers would save a great deal of time.

This can be a difficult task due to differences in contrast between the two images. An added problem is caused by occlusion. How will the software decide to delete pixels which are visible in one image and completely absent in the other?

Dedicated stereoscopic morphing programs, such as Evgenia Wassenmiller’s “Stereomorpher”, attempt to solve this problem using segmentation methods. [Gonzales & Wood, 2001; Russ, 2002] Figure 20 shows a stereo pair of a woman, before it is segmented. [Wassenmiller, 2003b]
Segmentation is the first step in generating the spatial information about the features in a scene. Edge detection algorithms are used to outline each image's features. By comparing pixels with equivalent intensity values on epipolar lines, their two-dimensional spatial disparities are measured. These values are used to generate a
grayscale depth map. The depth map is used to sequentially displace the related pixels from their initial position in the Left image to their final destination in the Right image.

But this solution is far from ideal. The results can sometimes take longer to compute than land-mark based methods and even then, the final morph is not perfect. Even Wassenmiller [2003b] clearly admits, "Generated views are often not ideal, and need some manual correcting." These problems are attributed to occluded features. As Liedtke [1993] points out:

This approach is sufficient for simple scene geometry without occluded areas but will fail when analyzing complex scenes like street views

Nonetheless, Wassenmiller seems to be heading in the right direction. As will be mentioned in the final chapter on areas for future research, a combination of feature morphing augmented by line morphing techniques may be the way to produce fast, high quality results.
CHAPTER 5

LINE MORPHING FOR LENTICULAR PRINTS

Pre-morph Preparation of Stereoscopic Pairs

Horizontal Alignment of Image Features

It is important that there be zero vertical parallax between the Left and Right images. [Ferwerda, 1990, p. 25] Even if the original stereo pair was recorded on a single photographic plate, it cannot be assumed that the images are perfectly registered. This is even more so if each image was recorded separately. It is particularly important to have all of the features aligned vertically if feature morphing techniques are used.

The alignment process must start with the original analogue images scanned in at the highest resolution that both the scanner and the computer can accommodate. High initial resolution will produce finished lenticular images with the highest visual fidelity.

Once the Left and Right images have been digitized, they should be image processed for alignment, blemishes, colour correction, setting the zero plane point and cropping. Adobe® Photoshop® is a widely available application that can accurately handle all of these tasks.

The above-mentioned processes can easily be achieved if both the Left and Right images are combined into a single document, with each image on its own layer. Using either special glasses or by free viewing, it must be verified that the Left image is
indeed the Left image. If the images are reversed, the three-dimensional scene will appear "inside out" or pseudoscopic. This is important to correct if the interlacing software stipulates a particular image sequence in order for the final lenticular image to be properly interlaced.

The alignment process is started by placing a horizontal guide onto a clearly visible feature on the Left image. This line is referred to as an epipolar line (each point in the Left image is restricted to lie on a given line in the Right image). The Right image's layer is moved manually until its similar feature is aligned with the guide. In Figure 22, the Right image's layer is aligned with the Left image's layer along an epipolar line.

Figure 22. Aligning the Left and Right images. An epipolar line (horizontal blue line) is a guide that is set on a significant detail on the Left image. The red arrows on the Right image, indicate the direction and distance that the same feature on the Right image must be moved in order to horizontally align it with the Left image. Note. Adobe product screen shot reprinted with permission from Adobe Systems Incorporated.
Next, it is important to find some features at the top and bottom of the Left image and determine if they are aligned with similar features on the Right image. If they are not, it may still be necessary to rotate and scale the Right image until every feature on it is accurately lined up horizontally with the same features on the Left image.

**Establishing the Picture Plane Zero Point**

There is no golden rule for this next step, however, it is easier for people to view stereoscopic images that appear behind the picture frame than images that float in front of it. Traditional stereoscopic photographic practice has also suggested that scenic images appear behind the picture frame [Ferwerda, 1990, pp. 133-134]. In addition, some morphing software insists that all pixels morph from one image to another in the same direction. [Wassenmiller, 2003a] This would not be the case if some features were in front of the frame and others behind it.

To set the picture plane zero point, the Right image, which is part of the same document file as the Left image, is moved horizontally until it is over top of the Left image. The Right image’s opacity is then reduced to approximately fifty percent. An identical feature should be found in both images that was closest to the original camera. The semi-transparent Right image is then moved until this feature on the Right image is sitting perfectly on top of the same feature on Left image. The zero plane of the stereoscopic scene has now been set. Figure 23 shows the registered Left and Right images. Notice that features at the zero plane are sharp and clear, whereas features furthest away and in the background look “double exposed” or blurred.
Figure 23. Determining the Picture Plane’s Zero Point. In this case, the zero point was set on the man in the right foreground. Notice how sharp he is compared with the other features in the background. Note. Adobe product screen shot reprinted with permission from Adobe Systems Incorporated.

The final step in setting the zero point is to return the Right image’s opacity to one hundred percent. By quickly toggling the visibility of the Right image on and off, it is possible to view the scene as if it were swivelling about the picture’s zero point.

Initial Cropping

The combined images are cropped to remove the overlapping edges. Cropping also facilitates the removal of extreme blemishes and colour problems. Nonetheless, the crop area should be made as large as possible, in order to maintain a large, high resolution image, which can be further cropped and down-sized later.
Removing Dust and Scratches

Adobe Photoshop has a variety of tools for manually fixing blemishes. These tools include dodge, burn, clone and saturation. However, what may be a straightforward repair job of a single photograph becomes much more complicated when dealing with a stereo pair. Not only must damaged features on one image be repaired to the same luminance and detail values as their counterparts on the other image, they must also lie at the correct depth relative to the immediately surrounding features. One way to partially alleviate this problem is to set the initial image resolution to as high a value as possible, make the necessary repairs and then later downsize to the final image resolution. As will be mentioned at the end of this thesis, this is an area for future research, since many old stereo photographs need significant repairs.

Colour Correction

It is important that the features of both images have equal luminance values. Otherwise, particularly if there are significant differences in brightness levels between the Left and Right images, binocular rivalry will result (as was illustrated by Figure 10 in Chapter 2). If feature morphing techniques are to be employed, it is even more important that pixels on one image have brightness levels similar to their counterpart pixels in the corresponding image.

Once again, Adobe Photoshop has a variety of image adjustment tools, which can be used either globally or selectively on an image. However, discussion of the full range of colour correction techniques is beyond the scope of this thesis. For those interested in these techniques, there is a large selection of books that deal specifically with these issues. [Eismann, 2004; Margulis, 2001; McClelland, 2002]
Creating Separate Image Files

The final step before morphing is to separate the layers into individual Left and Right image files that can be imported into the morphing software application. Often a batch script can be written which saves the separate images in the file format required by the morphing software application.

Morphing

Line Morphing with Elastic Reality

The earlier section on the principles of morphing describes a number of approaches to morphing one image into another. Theoretically, all of them will achieve similar results, depending on the amount of occlusion within the individual stereographs. However, the line morphing software package Avid Elastic Reality is used to illustrate the underlying principles of image morphing as it pertains to stereoscopic images.

Elastic Reality's User Manual is excellent and the application itself is intuitive and quickly gives rewarding results. Therefore, a detailed description on how to use the software, will not be provided. Instead, only the key points, which are important for producing a high quality lenticular image, will be discussed.

The Left image (the source) is imported into Channel A and the Right image (the target) into Channel B. Vector lines are used to trace features of the Left image. At this stage, the trace can be very crude. Figure 24 shows an initial tracing of the Left image of a woman in Channel A.
Figure 24. Rough line tracing of a woman’s outline. Note. © 2004 Avid Technology, Inc. All rights reserved. Avid and Elastic Reality are either registered trademarks or trademarks of Avid Technology, Inc. in the United States and/or other countries. Screen captures of Elastic Reality® software are provided courtesy of Avid Technology, Inc.

Fine details are captured by adding correspondence points. The more points that are added, the longer the final image sequence will take to render. However, the result will be a more accurate lenticular image. The correspondence points move the associated pixels from the source image towards the corresponding group of pixels in the target image. Adding more correspondence points results in greater depth subtleties. Figure 25 shows the tracing of the woman in Channel A after the addition of correspondence points.
Figure 25. Accurate correspondence points on a woman’s outline. Note. © 2004 Avid Technology, Inc. All rights reserved. Avid and Elastic Reality are either registered trademarks or trademarks of Avid Technology, Inc. in the United States and/or other countries. Screen captures of Elastic Reality® software are provided courtesy of Avid Technology, Inc.

Following the completed tracing of a feature in the Left image, the line is copied and pasted onto the Right image (Channel B). The newly pasted line should only be moved in a horizontal direction in order to line it up with the similar source feature. Normally this line will not fit perfectly because there will be edge position differences due to differing depth levels within the feature. These points must be manually moved horizontally until they correspond to their epipolar equivalents of the Left image in Channel A. Points should only be moved in a horizontal direction. Movement in a vertical direction means that the Left and Right images are misaligned, which will cause viewing problems in the finished lenticular. Figure 26 shows the pasted correspondence...
points before and after they have been moved to match the outline of the Right image's feature.

Figure 26. The image on the left shows the line from Channel A as it appears when it is initially pasted over top of the Right image in Channel B. The image on the right shows the same line after it has been adjusted to coincide with the Right image's equivalent feature. Note. © 2004 Avid Technology, Inc. All rights reserved. Avid and Elastic Reality are either registered trademarks or trademarks of Avid Technology, Inc. in the United States and/or other countries. Screen captures of Elastic Reality® software are provided courtesy of Avid Technology, Inc.

Next, the Channel A line is joined to the Channel B line. The correspondence lines connecting the two shapes should be perfectly horizontal. This assures that pixels in the Left image will follow a straight, horizontal path to their corresponding pixels in the Right image. As a result, horizontal integrity is maintained in all of the in-between frames of the morphed image sequence. Figure 27 shows the lines before and after joining.
The Problem of Occlusion

The situation where one object occludes the view of another object is a natural phenomenon that works as a monocular depth cue. An object, which may be in full view in the Left image, may be partially or fully occluded by another object in the Right image. The inverse of this situation can also be true. If the vector paths are not properly controlled when dealing with occluded features, horizontal and vertical distortions can occur, resulting in an animated blur in the final image sequence. Figure 28 shows the Left and Right images of a stereo pair. The sections highlighted in colour show the
areas that pose an occlusion problem. The trunk of the tree in the background is progressively occluded by the tree in the foreground.

Figure 28. Occlusion of a Background Feature. The coloured boxes highlight a feature in the Left image (red box) which is partially occluded in the Right image (blue box).

Note. Stereoscopic photograph courtesy of the Vancouver City Archives.
Figure 29 shows the image sequence of poorly morphed occluded features along with the lines used to morph the images.

![Figure 29](image_sequence.png)

**Figure 29. A Poorly Morphed Occlusion.** The lines from the Left image have been pasted onto the Right image without any modification. The result is a simple dissolve as well as unnatural warping of the occluding tree trunk in the foreground. *Note.* © 2004 Avid Technology, Inc. All rights reserved. Avid and Elastic Reality are either registered trademarks or trademarks of Avid Technology, Inc. in the United States and/or other countries. Screen captures of Elastic Reality® software are provided courtesy of Avid Technology, Inc.

The problem illustrated in Figure 29 is that the software does not know how to invent or dispose of pixels as they appear or disappear behind an occluding foreground feature. This is overcome by using carefully constructed morph lines. Figure 30 shows the correctly modified lines in the Right image. The oblique, angled line in the Left image was copied, pasted and horizontally aligned with its counterpart feature in the Right image. A new point was added to the Right image line where the angled line crossed the foreground tree's vertical line. This modified line was copied and pasted back into the Left image, with the original line being deleted. Returning to the Right
image, the top end point of the line was moved in a perfectly horizontal direction until it reached the vertical line of the foreground tree trunk.

The lower "C" shaped line was also copied and pasted from the Left image into the Right image. In the Right image, the ends were shortened until they touched the vertical line of the foreground tree trunk. This configuration insures that all pixels will move in a strictly horizontal direction, therefore maintaining epipolar integrity. Figure 30 also shows the resulting image sequence with the significantly improved morph sequence.

![Figure 30. A Satisfactorily Morphed Occlusion.](image)

Rendering the Morph Sequence

During the course of the tracing process, Elastic Reality allows the developing image sequence to be previewed as a movie. The movie should reveal a smooth animated swivel from the Left to the Right image. This is one of the major advantages of
line based morphing methods. Previewing the in-process morph allows for quick and
easy line adjustments to ensure the accuracy of the final image sequence.

Another advantage of line morphing is that low resolution images can be used for
the initial tracing process and later replaced with the higher resolution images which take
longer to render but produce higher quality images. This allows for quick assessments
of the tracing process and yet gives the high quality necessary for the final rendering.

Once all of the features have been traced and joined, it is a simple matter to
render the image sequence. The number of frames to render will depend on the pitch of
the lenticular lens sheet and the resolution of the printer.

**Pitch and Resolution**

There are a variety of manufacturers producing lenticular sheets which can be
directly printed onto or glued to a paper print. Micro Lens Technologies Ltd. is a
company that produces these sheets for a variety of display environments. It is
important to know the environment in which the final 3D images will be displayed. The
size of the final image and the public viewing distance determines the number of
cylindrical lenses per inch.

Table 1 is a chart derived from the Micro Lens website [Micro Lens, 2002] which
helps determine the best screen pitch or lenses per inch (lpi) for the ideal public viewing
distance from a lenticular display.
The resolution of the printer will determine the maximum number of interlaced frames that can be printed behind the chosen lenticular sheet. Each cylindrical lens can have two or more frames behind it. Figure 31 shows the arrangement of ten frames (each with its own colour) interlaced underneath a cross-section of a lenticular sheet.

Table 1. Viewing distances and the recommended pitch of the lenticular screen. [Micro Lens, 2002]

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Figure 31. Cross-Section of a Lenticular sheet with ten interlaced images underneath each individual lens.
The resolution of an inkjet printer is described by the maximum number of dots it can print per inch horizontally and vertically. Therefore, an inkjet printer with a theoretical maximum resolution of 1200 x 600 dots per inch (dpi) can print 1200 dots per inch horizontally and 600 dots per inch vertically.

If the pitch of the lenticular screen is 60 lenses per inch, then the maximum number of dots that can be placed within the width of each lens is $1200/60 = 20$ dots per lens.

This means either twenty frames, one dot wide, can be interlaced behind each lens or; ten frames, two dots wide, can be interlaced behind each lens. The more viewpoints or recorded frames of a scene, the more fully three-dimensional it will appear in the final lenticular picture. It should be noted however, that this is a theoretical value. Printer realities may dictate otherwise. Most inkjet printers can only resolve ten, one pixel wide, images per lenticule. Only printed test images from the printer will determine the upper limit of the number of frames that can be practically resolved behind each lenticule.

**Pitch Test**

Due to variances in the manufacturing process, a 60 lpi lenticular sheet will not necessarily be exactly 60 lpi. A printed pitch test has to be conducted in order to find the precise pitch of the lenticular sheet. All developers of lenticular interlacing software include a pitch test feature. Figure 32 is the dialogue box for the Pitch Test found in PhotoProjector 1.6 which is a software package available from Evgenia Wassenmiller [2003a].
Figure 32. Dialogue Box of the PhotoProjector Pitch Test. Note. PhotoProjector product screen shot reprinted with permission from Evgenia Wassenmiller.

Figure 33 shows the resulting printout of the pitch test for a lenticular sheet rated at 60 lenses per inch and a maximum printer resolution of 1200 horizontal dots per inch.

Figure 33. Printout of PhotoProjector’s pitch test for a 60 LPI lenticular screen.
The final step of this test is to place the 60 lpi lenticular sheet over top of the printout. The sheet is adjusted and registered until one of the horizontal pitch strips appears either solid black or white. This represents the approximate lens pitch setting. Lenticular images interlaced at this pitch setting will properly reconstruct the depth relationships within the original scene. Chapter 7 describes the final calibration for adjusting the completed interlaced image.

*Post-morph Image Processing*

**Image Sequence Resizing**

As mentioned, the image sequence should be rendered at the highest possible resolution. This allows it to be downsized to fit a wide range of lenticular sheet sizes. However, due to different sheet formats, selective cropping may be necessary. This poses the problem of ensuring that each image in the sequence is cropped in the proper position.

This is achieved by opening the first and last images of the sequence in an image processing application such as Adobe Photoshop. By cropping with a fixed aspect ratio, the selection marquee can be proportionally drawn to fit the preferred view of the first image of the sequence (usually the Left image). This selection is saved as an alpha channel. Figure 34 shows this first step in preparation for cropping.
Figure 34. An alpha channel crop mask. The red part of the image is the mask that is used to crop the image. This mask is saved as an alpha channel so that it can be accurately duplicated to crop the other images of the morph sequence. Note. Adobe product screen shot reprinted with permission from Adobe Systems Incorporated.

The entire alpha channel is then copied and pasted into the open document of the Right image of the sequence. If the composition is acceptable in both documents, the alpha channel is pasted into the other images of the sequence. Finally, all of the images are cropped using the selection created by this alpha channel mask. This ensures that all of the images are still correctly aligned and registered.

The next step is to resize all of the images to the final resolution. In many cases this will be 72 dots per inch. For example, if the final lenticular image size is eight inches by 10 inches, the final image size of each sequential image will be 576 pixels by 720 pixels if it is assumed that there will be only one row of pixels from each of the ten
images behind each of the lenses. Bicubic interpolation, during the resizing process, is used to achieve smooth image rescaling.

**Sharpening**

The Chapter 2 section on stereo acuity pointed out that high contrast or sharply focused images produce stronger stereoscopic effects than low contrast or blurred images. Both the morphing process and the bicubic image downsizing produce images with soft edges. This is rectified by sharpening each image by the same amount. Over sharpening must be avoided since it can produce halo effects as well as image distortions in non-horizontal directions.

The entire post-morphing process can be automated so that all of the images can be batch processed. Batch processing greatly speeds up this phase as well as eliminating any inconsistencies that could arise from human error when processing one image at a time.

**Animating the Image Sequence**

Once the sequence has been rendered, it can easily be converted into either a short digital movie or an animated GIF. By constructing the animation to loop back and forth, the swaying scene displays all of its depth information over time. As mentioned earlier, the animation can be used to find faults in the morphing process, but more importantly it can be either streamed to the internet or used as an alternative display to allow people with stereoscopic vision abnormalities to appreciate the scene's depth.
To make a lenticular print from the image sequence, the images have to be correctly interlaced. What used to be done photo-mechanically, can now be done digitally. The process involves taking a corresponding vertical strip from each image and placing them beside one another. For example, the first column of pixels of the first image is placed beside the first column of pixels from the second image which is placed next to the first column of pixels from the third image and so on. Then the second row of pixels from each image are placed sequentially beside each other. If there are ten images, then the first column of pixels from each of the images must fit within the width of one lenticule of the lenticular sheet. This arrangement insures that the final lenticular picture will correctly reconstruct the original scene’s spatial relationships. Figure 31 on page 51 shows the relationship between the interlaced image strips and the lenticular sheet.

Software

There are several commercially available software packages that interlace multiple images to produce a lenticular print. [LCK, 2003; Wassenmiller, 2003] They all use similar algorithms to get the job done. For this reason I will focus this process on RefractiveMatrix 1.11 and PhotoProjector 1.6, which cover all of the important features needed to produce high quality prints. [Wassenmiller, 2003]

Starting the interlacing process requires the entry of specific data about the characteristics of the lenticular sheet that will be laminated to the printout.
RefractiveMatrix 1.11 calculates LNT files for the interlacing program PhotoProjector 1.6. LNT files contain the information about the lenticular sheet as well as the images.

Figure 35 shows the default dialogue box for RefractiveMatrix 1.11.

![RefractiveMatrix 1.11 Default Dialogue Box](image)

Figure 35. RefractiveMatrix 1.11 default dialogue box. Note. RefractiveMatrix product screenshot reprinted with permission from Evgenia Wassenmiller.

First, the default data entries have to be changed to the values of the actual lenticular screen. Using values supplied by Micro Lens, the lenticular screen's manufacturer:

- Curvature radius of lenticular lens: 0.35 mm
- Thickness of lenticular sheet: 1.22 mm
- Refractive index of lenticular sheet: 1.52

The pitch or lenses per inch was determined by the Pitch Test to be 59.99 lpi.

Next, information is added about the images.
The number of pixels per lens will be 10 (one for each of the ten frames).

The width of each frame is 203.2 mm (8 inches x 25.4 mm).

The height of each frame is 254 mm (10 inches x 25.4 mm).

The number of camera viewpoints is 10.

The distance between each of the views was calculated to be 7.2 mm (If the Left and Right views are 65mm apart and there are 8 views between them, then there are 9 spaces between the 10 viewpoints. 65mm/9spaces=7.2mm/space).

The distance between the finished lenticular image hanging on a wall and the person viewing that image is arbitrarily set to 1000 mm (1 meter).

Figure 36 shows the RefractiveMatrix dialogue box before it is calculated and saved as a LNT file which will be used by PhotoProjector.

![RefractiveMatrix 1.11 dialogue box for 10 views, 59.99 lpi, LNT file.](image)

Figure 36. RefractiveMatrix 1.11 dialogue box for 10 views, 59.99 lpi, LNT file. *Note.* RefractiveMatrix product screen shot reprinted with permission from Evgenia Wassennmiller.
Interlacing the Rendered Frames

After the data for the lenticular sheet and the viewpoints are entered, it is an easy task to interlace the image sequence to produce a lenticular printout. The recently created LNT file is loaded into PhotoProjector 1.6, which in this case is the Desktop file “8x10.lnt”. This file automatically generates the information displayed in the “Lenticular image parameters” window, as shown in Figure 37.

Figure 37. PhotoProjector 1.6 dialogue box with loaded LNT and image files. Note. PhotoProjector product screen shot reprinted with permission from Evgenia Wassenmiller.
The individual frames are loaded by simply selecting the "Load image files" button. The width and height of the output file is automatically computed. All that remains is to render and save the final interlaced image, which may take some time to interlace, depending on the file size of the sequential frames and the computer's processing speed.
Printing

Figure 38 is a scaled down version of an image sequence rendered and interlaced using the foregoing process. Notice that objects furthest away from the zero plane appear "blurred" while those closest to the picture plane appear "focused". This is similar to the layered image seen while establishing of the zero point in Chapter 5.

Figure 38. Scaled down version of the interlaced image produced by PhotoProjector 1.6
The image is best printed on heavy, high gloss, inkjet compatible paper. This ensures that the image will be as flat and as sharply resolved as possible. Kodak's Ultima Picture Paper fits this criteria. It's 8.5 x 11 inch high gloss paper is 10 mil. thick.

**Printer Resolution**

High quality and high resolution printers produce the best lenticular prints. Figure 39 compares the ideal computer screen image (far left) with two images produced by two different inkjet printers. The middle image is a scan of a print produced by a photo inkjet printer with a resolution of 4800 x 1200 dots per inch (dpi) and an ink droplet size of 2 picoliters. The image on the far right is a scan of a print produced by a basic inkjet printer with a resolution of 1200 x 600 dpi.

It can be clearly seen that the middle image most closely mimics the quality of the ideal, screen-captured image. The print produced by the basic inkjet printer (far right) produces a final lenticular image with poor image details and therefore less depth effects.

![Figure 39. Comparison of original digital image to printer outputs. The image on the far left is a screen capture of an interlaced image. The other two images are the printouts of the same image produced by different printers. The middle print was made by a photo inkjet printer whereas the far right image was made by a basic inkjet printer.](image-url)
Refined Pitch Calibration with the Printed Image

After printing, the accuracy of the image is checked by placing a non-adhesive lenticular sheet over the print. If the print cannot be successfully aligned (moiré lines appear) it means that the pitch of the lenticular sheet is slightly different than what was determined by the initial pitch test. Instead of re-interlacing the frames with a new pitch value, the finished image file can be reset to a new lens per inch setting by using an image processing application, such as Adobe Photoshop.

For instance, in order to change an image that has been previously interlaced at 60.00 lpi to 59.97 lpi, without reinterlacing the image, divide the original lpi (60.00) by the new lpi (59.97) and multiply by 100 per cent. Therefore: $$\frac{60.00}{59.97} = 1.0005 \times 100 = 100.05\%.$$ Using Photoshop's “Image Size” dialogue box, input the new calculated percentage (100.05%). Photoshop will automatically calculate the new size. This process may also be necessary when printing from a new printer or using new paper stock.

Another printing problem is that, even though lenticular lens materials are identified by the number of lenses per inch (lpi), the exact number is usually slightly different. Using the 60 lpi material as an example, the pitch test determined an actual pitch of 59.97 lpi. Although this is not 60.00 lpi, it is still considered 60 lpi material. Because the material is not exactly 60.00 lpi, an optical banding effect can occur in certain prints because the interlaced number of pixels per inch is not an exact multiple of the printer's resolution. For instance, the final image was interlaced at exactly 60 lpi and printed by a 600 dpi printer, optical banding would not be a factor because 60 can be divided equally into 600. If, however, the image was interlaced at 59.97 lpi and printed
to a 600 dpi device, then optical banding would occur because 59.97 cannot be divided equally into 600.

To counteract this effect, the resolution of the final image is first increased to twice the number of pixels per inch for the intended final output resolution. The intended final output resolution should be an even multiple of the printer’s exact resolution. For example, if the image is created at 600 pixels per inch (ppi) and interlaced at 59.97 lpi then the final image size will not be 600 ppi but rather 600.3 ppi (600 x 1.0005). In order to correct the resolution and eliminate optical banding, the image’s resolution is increased to 1200 ppi and then immediately decreased back down to an exact 600 ppi. The image’s horizontal and vertical proportions must be constrained and interpolation must be bicubic.

The reason for increasing the resolution is to ensure that there are enough pixels to readjust the resolution down to get a smooth transition. This eliminates the banding effect. In order for this to work effectively, a 2 to 1 relationship between actual file size (in ppi) and increased file size (also in ppi) is required. For example: 600.3 ppi to 1200 ppi and then back down to 600 ppi. [Micro Lens, 2002]

After printing, allow the printout to thoroughly dry before laminating. *This cannot be stressed enough.* Even a partially wet print cannot be properly aligned with the lenticular sheet. The drying process may take up to several hours, depending on the ambient temperature and humidity.
Laminating

Aligning the Lenticular Sheet

It is important to properly align and adhere the lenticular sheet to the print. If the lenticular sheet is misaligned, moiré lines will appear in the final picture. The lenticular sheet must be adjusted until all moiré lines disappear. Only then will all of the picture appear three dimensional, even when the viewer moves their head.

Lenticular sheets, with an adhesive backing and an adhesive protector, can be purchased from a variety of manufacturers. Micro Lens uses a silicone adhesive protector because paper adhesive protectors leave a strong adhesive pattern that is easily detectable in the final mounted print.

The mounting process is started by attaching pieces of masking tape to the adhesive protector in the upper right and left hand corners (see Figure 40). These tabs are used to peel off the protector during the lamination process.
Figure 40. Removing the adhesive protector with tape to expose the adhesive on the back of the lenticular sheet. The upper, removable lens cover, is used to protect the delicate surfaces of the lenticules. It is held in place by static forces and can be easily removed after the lamination process.

Next, the thoroughly dry, interlaced inkjet print is placed face-up on the laminator’s bed and a few centimeters away from the laminating rollers. The print’s interlaced lines are aligned perpendicular to the laminator’s rollers.

The adhesive protector is peeled back using the masking tape to reveal about 2 cm of adhesive. The lenticular sheet is then placed, with the adhesive side down, on top of the interlaced print. A piece of 6mm thick glass plate is placed on top of the lenticular sheet to flatten it into position. This allows the image to remain visible during the alignment process. Since the adhesive protector is between the bottom of the lenticular sheet and the print, the lenticular sheet can be properly registered with the print. Figure 41 shows a print and lenticular sheet ready to be laminated by a Xyron 850 cold laminator.
Figure 41. Interlaced print, lenticular sheet, glass plate and Xyron cold laminator are ready for final lamination

After tacking the exposed adhesive edge of the lenticular sheet to the top of the print, the glass plate is removed and both the lenticular sheet and the print are pushed up against the nib of the laminating rollers.

The masking tape tabs are used to slowly pull off the adhesive protector while feeding the print and the lenticular sheet into the laminator (Figure 42). The adhesive protector must be removed at a steady pace in order to avoid sticking the print to the lens sheet before they reach the rollers. This can be accomplished by having no more than 5 cm of exposed adhesive between the peeled back adhesive protector and the nibs of the laminating rollers.
Figure 42. Removing the adhesive protector during lamination

The process is finished when the adhesive protector has been completely pulled off and the laminated print has come out the other side of the laminator.
CHAPTER 8
DISCUSSION OF RESULTS

The process of converting stereographs into lenticular images is viable. For the first time, viewers can appreciate the original scene's spatial information without requiring special viewing glasses. The process of sequential image morphing and interlacing the images to produce a lenticular picture also overcomes the original stereograph's "card boarding" effect.

The only drawback to this conversion process is that there is a loss of fine details in the lenticular image. Some of this is due to the limitations of inkjet printer resolutions and their inability to draw extremely fine lines of less than 1 picolitre in size. No doubt, this will be solved as printing technology continues to advance. However, the lenticular screen also contributes to a loss of perceived resolution. Specular reflections, from the columns of cylindrical lenses, produce a visible artefact or noise that detracts from the image. This can be partially alleviated by placing a sheet of non-glare glass in front of the lenticular picture.

A major difference between the stereoscopic pair and its lenticular image is that all of stereograph's features are in sharp focus regardless of their spatial position in the scene. This is not true for the lenticular image. Due to the focal length properties of the lenticules, there is noticeable blurring of features that are furthest away from the zero point of the picture plane. Viewers will perceive some of this blurring as atmospheric perspective that naturally occurs with outdoor scenes, however it is a noticeable problem with close-ups or indoor scenes. Close-up images look as if they were recorded with a camera that had a very narrow depth of field whereby much of the picture appears out of focus.
The animation of the image sequence overcomes both of the problems of specular noise and blurring. It is also an easy way to broadcast, via the internet, the original scene’s spatial relationships. Conveniently, this is an intermediary step in producing the lenticular print and is a direct result of the morphing process.

The line morphing process, outlined in this thesis, produces excellent autostereoscopic lenticular displays with some types of stereo pairs. Urban scenes filled with lots of vertical and horizontal surfaces are easily handled by this method. Rural scenes, filled with vegetation and non-linear lines, prove to be more difficult.

Due to the manually intensive nature of edge tracing a complex scene, it is next to impossible to capture all of the subtle depth details in vegetation. At some point, even with city scenes, decisions have to be made about the level of detail one is willing to trace. Even an urban scene may require several hours, if not days, to trace satisfactorily. Occluded features require even more effort if they are to be accurately morphed.

Although Avid’s Elastic Reality produces high quality finished images, with strong depth effects, it tends to be cumbersome for producing lenticular dedicated morphs. Tracing the outline of a feature and then having to go back and insert correspondence points, seems like an unnecessarily extra step. This negates any attempt to speed up the process by using dedicated bitmap to vector tracing software (such as Adobe® Streamline™). Even though these paths can be directly imported into Elastic Reality, all of their correspondence points still have to be set manually.

A morphing technique that would speed up this process would be greatly appreciated. Feature morphing seems to be the best method to try, even though it does not always produce reliable results. Wassenmiller’s “Stereomorpher” is not only slow, but it has great difficulty in dealing with occlusion problems. It can successfully morph
human faces, simple floral arrangements and other scenes that have features that gently slope back from a central point. In many cases the results are comparable to point morphing with meshes. Both Wassenmiller’s feature morphing and CHV Electronic’s point morphing applications have trouble with resolving features which fold either on top of or underneath other features.

Therefore, of the three digital morphing strategies that are currently available, the line morphing technique described in this thesis offers the greatest flexibility in producing a wide selection of high quality, lenticular pictures from stereoscopic photographs.
CHAPTER 9

CONCLUSIONS AND FUTURE RESEARCH

This thesis was written with the intention of setting out the principles underlying lenticular images and of providing a "user manual" for producing high quality lenticular renditions of stereoscopic photographs. To the best of our knowledge, this is the first illustrated description of the entire process. Parts of this process are scattered throughout the literature, however, none of them describe every step. With the proliferation of high speed personal computers and inexpensive yet high resolution photo ink jet printers, we will anticipate a growth in the production of customized lenticular images.

In order to solve the problem of accurately producing lenticular versions of historic stereograms, it will be necessary to faithfully replicate all of the depth information inherent in the original photographs. Each of the morphing methods described in this text have their limitations. Line morphing is the most successful at achieving the desired results, but it is painfully slow in dealing with complex scenes. Feature morphing could automate some of the work, but it has problems with resolving occluded features.

An area of further research would be to explore the feasibility of starting the morphing process with a feature morphing application and correcting the unresolved occlusion problems with a line morphing application. The line-morphed regions would then be composited with the feature-morphed image sequence. Automating any of the morphing process would definitely reduce some of the drudgery inherent in the traced, line morph method.
Chapter 5 described Elastic Reality's repetitive two-step process of edge tracing. Dedicated, stereoscopic, line morphing software could be written to reduce this method to only one step. Indeed, an application built with the sole purpose of producing lenticular images from stereo photographs could conceivably combine feature morphing, line morphing and interlacing within the same software package.

An interesting by-product of this research is the movie of the morphed image sequence. Not only can it be used as a diagnostic tool for assessing the accuracy of morphed occlusions; it has the added advantage of mimicking the motion parallax of the scene. For the first time, people who have trouble with stereopsis, can appreciate the depth inherent in these early stereographs. This also provides a way to broadcast these images online without the end user requiring special glasses.

Besides morphing, there are other research topics that would involve stereoscopic image processing. This would include the repairing of damaged stereo pairs, particularly pairs where one image is missing a detail found only in the other image. Accurately cloning a detail from one image to another, with correct depth relationships, has not been explored. This problem is new, because prior to this thesis, it was not viable to cosmetically repair an historic stereographic pair which few people would view. With the chance that these important images would now be put on public display, repairing them becomes a major consideration that goes beyond the usual 2-D photo restoration techniques.

A large part of this thesis focused on outputting the final image as a lenticular print. However, there are current hardware developments that allow these images to be autostereoscopically displayed on special computer screens. [Stereographics, 2004; Sharp, 2004] What are the problems of converting entire stereoscopic movies into
lenticular imagery which can be viewed on these monitors? Needless to say, the process will require dedicated software which can quickly and accurately solve occlusion problems. This also introduces the issue of morphing colour images, which was not directly addressed by this paper.

Even with technical advances in this field, will there be a consumer demand for this type of imagery? Consumer and market research studies are needed to determine if people will want to visit museums to view lenticular pictures, and thereby validate the costs in producing them. Will people want to buy smaller versions of the museum displays for their own home or collection? The answers to these last questions will no doubt determine the pace of technical developments.
REFERENCES


