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New advances in computer-generated barrier-strip autostereography

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Abstract

This paper discusses (1) a new proofing method of printing Cibachrome from monochrome films, producing higher saturation, spatial resolution, and dimensional stability; (2) experiments with inks and materials for mass printing of barrier-strip and lenticular autostereograms; (3) photographic enlargement and barrier-strip scaling; (4) techniques for combining photographs of real objects with computer backgrounds; and (5) the mathematics of projection and interleaving cylindrical (non planar) autostereograms producing up to a 360° viewing angle.

1. Introduction

1.1 History

The viewing of stereo images has been understood since Euclid in 280 A.D., and has been used in drawing since circa 1600. Photography, however, made stereography a practical and sometimes necessary technique for visualization. Photographic methods of producing autostereographic images have existed for many years.

(Art)^n, in collaboration with the Electronic Visualization Laboratory and other scientific laboratories, has been producing computer generated PHSColograms™ since 1984. We have used a photographic method for producing images, and we developed a computer generated method to increase the quality of our imagery.

1.2 Description of the computer barrier-strip method

The barrier-strip method allows viewing of N different views of an object. These views can be computer generated or photographed from *real time objects* . This process cuts each view into vertical columns, interleaves the columns, and positions them behind the slits of a barrier screen. The eye then sees the images through these slits. The position of the eye determines which view the observer sees.

Although such images may be produced by a photographic method, we have developed a computer interleaving method which we call the Stealth Negative™ method. A computer is used to interleave the images and write them onto the film. These images may be either computer synthesized or photographed and scanned into the computer.

The output is done on a high-accuracy output scanner associated with the graphic-art prepress industry, specifically a Crosfield™ scanner. The device produces four high contrast monochromatic films, representing cyan, magenta, yellow, and black, (CMYK) which together produce the final image. The barrier screen is also produced on the output scanner, which guarantees a perfect match between the image and the screen. (Sandin, et al, 1989)

2. New Proofing Methods

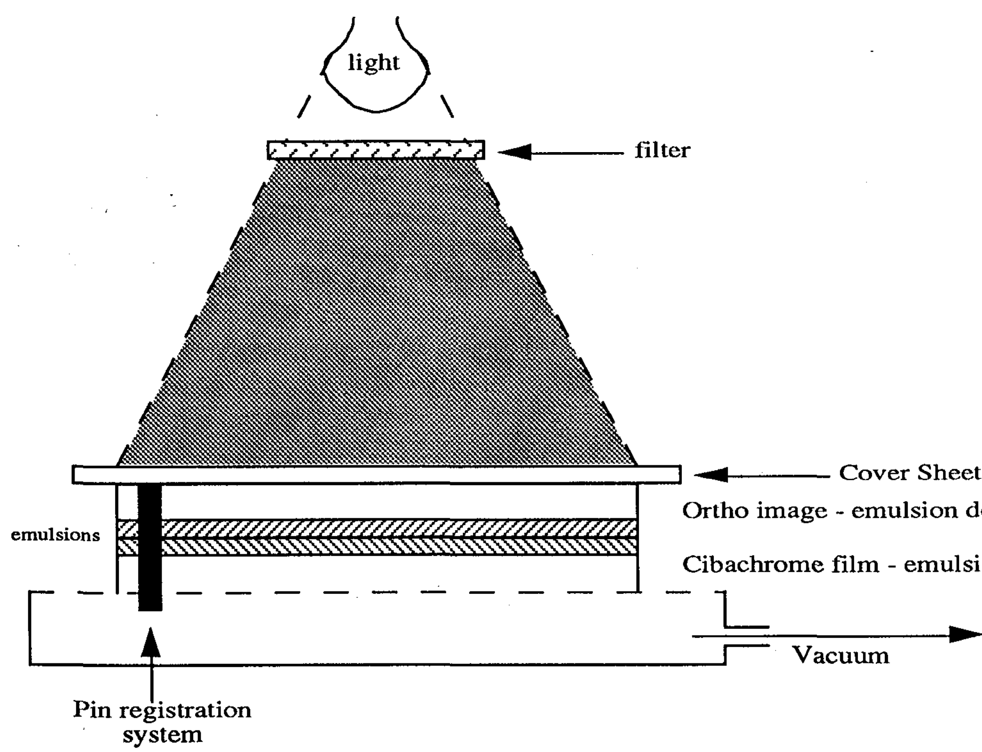
2.1 Cromalin proofing

Until quite recently, we used the Cromalin™ prrofing method on our output films exclusively. Cromalin is an encapsulated photosensitive polymer adhesive. This adhesive is laminated by heat to the substrate. It is then exposed to light through the positive film which was output by the scanner, which hardens the photopolymer and leaves unexposed areas receptive to a dye toner. The proof is laminated and exposed four times, with four different dyes, one for each of the subtractive colors (cyan, magenta, yellow, and black).

Although Cromalin responds outstandingly on the heavy stock paper ordinarily used in graphic arts, when applied to the translucent styrene substrate required by our process, it becomes *dimensionally unstable:* that is, it changes shape. This is unimportant at a low image pitch, such as 45 or 31 lines per inch, which correlate to the use of 9 and 13 images respectively. However, at high pitches, such as 80 lines per inch (5 images), this dimensional instability can cause moire patterns. Although precise for the usual needs of graphic arts, the powder has insufficient resolution to meet all of our needs. However, Cromalin's color response is very similar to that of printing methods, allowing a preview of an image which is to be mass produced.

2.2 Cibachrome proofing

We have now switched to Cibachrome™ film as our primary means of creating small runs of images and proofing. We register three of the four positive output films from the scanner, discarding the black channel, punching and/or tabbing them to allow accurate pin registration. We then contact print the films, exposing each color separately, using the complementary additive color corresponding to each subtractive color: The yellow channel is exposed with blue light, the magenta with green light, and the cyan with red light. This is done in an open-face vacuum frame with a cover sheet. The film is then developed by normal means.



Open face vacuum frame with cover sheet

Our barrier screen, which was produced originally on the output scanner, is photoduplicated. A barrier screen of a given pitch need only be scanned out once; photoduplication of barrier screens reduces use of the scanner, and hence, the cost of the process. The barrier screen is then hand-registered and laminated to Plexiglas™ along with the finished Cibachrome print on the opposite side.

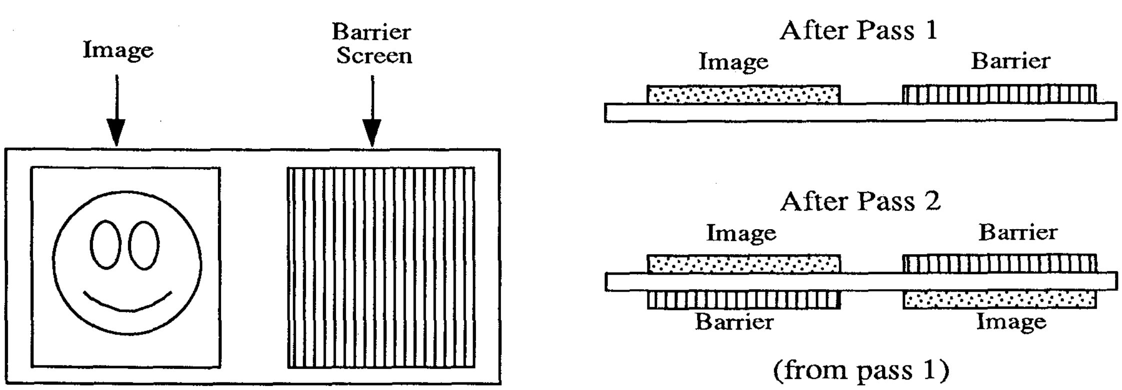
Cibachrome has greatly enhanced our image quality. First, we have better color response, and greater color correlation between our computer screen image and the final product. With Cromalin, we had to convert a three-color system (RGB) used in the computer to a four color system (CMYK). Cibachrome does not stretch or shrink significantly in the developing process, so we no longer have problems with dimensional stability. Cibachrome has a much longer life span than Cromalin, and higher resolution, which gives us better image fidelity. This has allowed us to increase the possible depth in the image. It is also less expensive and faster to produce than Cromalin.

3. Experiments with Ink and Materials

3.1 Barrier-strip printing

We would like to avoid hand lamination in the mass production of these images, since it is time consuming and prone to spoilage. When an image is improperly laminated, it must be thrown out. It is possible to avoid hand laminating by printing both the barrier screen and the image directly onto both sides of a single sheet of plastic, preregistered. The image is printed in four colors on one side of the plastic, and then the barrier screen is printed in black on the other side. A fifth color, white, may be added to the side with the image on it, to provide diffusion for backlighting. This would be applied as the final color across the back of the whole image, and it replaces the sheet of diffusion material which we normally attach to a Cibachrome image. The thin film allows for a wide viewing angle and provides reasonable depth. This is a very cost-effective method of producing these images, comparable in expense to any other high-quality, full-color printing. However, the barrier screen must be printed with extreme precision, requiring the use of the most accurate printing presses available. Furthermore, the barrier screen pass must produce significant ink density (D_{max}) in order to stop enough light. If the light is not sufficiently blocked, the viewer will see all images from all positions, and the stereo effect will not work. We are currently experimenting with several ink/plastic combinations to find the one with the greatest D_{max}.

In order to alleviate this problem, we are also working with a new method to increase D_{max}. We print the images two at a time, side by side. In the first pass, the image is printed on the left and the barrier screen on the right. The barrier screen is printed with a full four colors, providing greater density than with one color. The images printed in this pass are flipped over and run through the press again. The barrier screen that was on the top of the plastic on the right is now on the bottom of the plastic on the left. The image that was on top on the left is now on the bottom at the right.



Two pass printing system

Bear in mind that in normal printing, the printer wishes to put as little ink on the paper as possible, in order to keep the presses running smoothly and to enhance image quality. Too much ink can produce a "dirty" image, so printers also use *undercolor removal* to reduce the amount of ink used. For a barrier screen, we wish to put as much ink as possible on our plastic. This is a departure from traditional uses of printing press technology.

We are also experimenting with silkscreening the barrier-strip grid. Standard printing would be used for the image, but a silkscreen would be used to finish the piece. This still avoids the need for hand registration, has greater precision and more density than printing, but is more expensive and difficult, and would be used for smaller runs.

For runs between that of silkscreening and single-image proofs, we can mass print the image and laminate a photoduplicate barrier screen by hand. This avoids the cost of Cibachrome, but still provides the precision of a photographic barrier screen. It may be possible to construct a device to laminate photographic barrier screens automatically.

3.2 Lenticular printing

Bear in mind that these images must all be backlit and viewed in a lightbox. While suitable for many applications, some applications preclude the use of artificial backlighting, such as the cover of a magazine or a cereal box. For these applications, a lenticular grid replaces the barrier screen. Lenticular material allows light both into and out of the image, removing the need for expensive backlights.

A lenticular grid bears the same relation to a barrier screen that a lens camera has to a pinhole camera. The slits in the barrier screen are replaced by a series of vertical cylindrical lenses. Whereas the slits in a barrier screen block light, thus preventing images from being seen and reducing brightness, a lenticular focuses light, still controlling the view, but having little effect on brightness.

Previous lenticular methods have involved manufacturing lenticular material (or buying material already available) and creating an image to match the material. This is difficult, time consuming, inaccurate, and impossible given the nature of our output method. Our scanner is limited to a given number of dot densities, the highest of which is 400 dots per inch. In order to match this, we have had lenticular material manufactured to our specifications to match our scanner. This allows a better fit of the lenticular grid and autostereogram image than with previous methods. Our material was designed for a 5 image piece (which is a low-sounding number, but sufficient). 400 dots per inch divided by 5 images should produce a pitch of 80 lines per inch: however, measurement has shown the actual value to be 81.3 lines per inch.

Our lenticular material is of a higher quality than material currently available, which has a tendency to make images look *plasticky*. The plastic was also tested before extrusion for ink receptivity, as well as for resistance to picking and scratching.

In using the lenticular material, we simply print the image on the smooth side, giving a finished image with no lamination required.

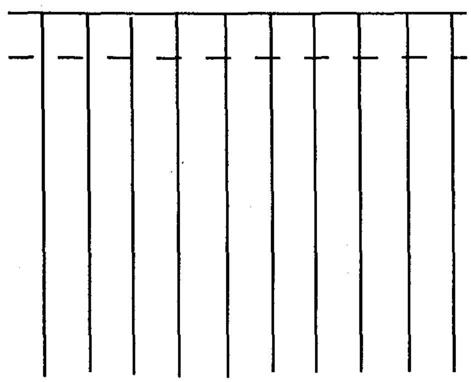
Although the 5 image restriction of this material sounds limiting (particularly in comparison to the 9 and 13 images used normally), it is possible to photoreduce a larger image, with more multiplexed images (and hence a coarser pitch) down to match the pitch of the material. It would seem that this would be a daunting task, since the reduction must be made to a precision on the order of ±.0001 inch, but we have developed what we feel is a unique method of finding the correct reduction. We place the lenticular material on the reduction easel and project the image onto it. The image then reflects through the material and will have a visual band on it if the reduction is incorrect. The reduction factor is then carefully changed by hand until the banding is gone, guaranteeing a perfect fit. This photoreduced image can then be reseparated and mass printed onto the lenticular material for greater quality.

4. Photo Enlargement

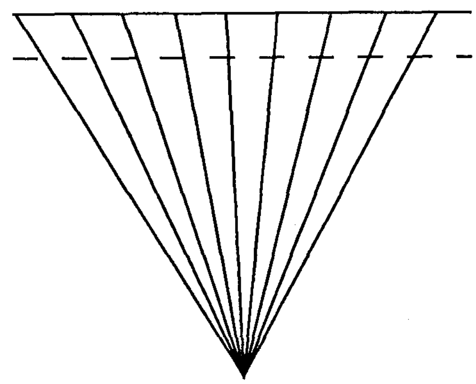
Once the contact Cibachrome print master has been produced, it may be enlarged by traditional methods. While a 20"x24" master is produced for single copies at the highest resolution, an 11"x14" master must be used for enlargements, since the largest enlarger we have access to has an 11"x14" chase; normal enlarging equipment rarely will accept an input size of over 8"x10", and a 20"x24" chase is almost unheard of. Our maximum enlargement is 20 feet by 5 feet. Larger images can, of course, be made by putting smaller ones side by side, although we have not had to test the quality of this method.

The barrier screen is enlarged by the same magnification as the image. However, a barrier screen of exactly the same pitch as the image assumes a long viewing distance, since all lines coming out of the barrier screen are parallel. If the barrier screen is enlarged slightly less than the image, that is, if it is reduced relative to the image, this corrects for parallax and allows for a closer viewing.

Barrier screen same pitch as image



Barrier screen higher pitch than image



The enlarged image and barrier screen are coarser than the originals. For very large images at close viewing distances this can be undesirable, but since one ordinarily views a large image from far away, the difference is not noticeable. It is, in fact, rather surprising that the difference between a 9 image 11"x14" blown up to 20"x24" and a 13 image 20x24 master can only be seen with difficulty by a trained observer, and most of the differences are due to the slight generation loss inherent in any photoduplication system.

Using a photoreduction method similar to that used for lenticulars, it is also possible to reduce a 20"x24" master to 11"x14" and then enlarge it. This would effectively double the resolution of our scanner, from 400 dpi to roughly 800 dpi. This would allow us to increase the pitch of finished blowups, as well as the number of interleaved images.

5. Real objects with computer backgrounds

When we do computer-interleaved autostereograms of real-time photographic subjects, we do so by shooting multiple views of an image using a high-quality view camera and scanning the images into the Crosfield system. At present, we use a Swiss Arca camera with 4"x5" film.

Since the images have been input into a computer, they may then be manipulated in ways familiar to those in computer-aided graphic arts. Unlike traditional photographic methods, where retouching is done entirely by hand, it is possible to process each image in exactly the same way, maintaining the correlation between images. This permits us a wealth of options heretofore unavailable in this medium. One could combine live objects with computer-graphic objects, or use live objects in a computer-generated scene.

We have already used the computer to matte a scanned background into a photographic image. The background was scanned from a stock photographic transparency, and foreground was shot on black. The black background was removed by a combination of image processing and hand touchup techniques, entirely in software. A matte, was produced for each image in digital form, and the background for each frame was matted in. We have also used this method to add typeset text in the foreground of an image. It is interesting to note that the apparent depth of a flat image may be easily selected by simply shifting it from frame to frame. The direction of motion selects whether the image is in the foreground or background, and the amount amotion selects how far. This image lacks, of course, depth cues of its own, but this still allows us to force the maximum depth for a background, helping the viewer understand the mid- and foreground.

6. Cylindrical autostereograms

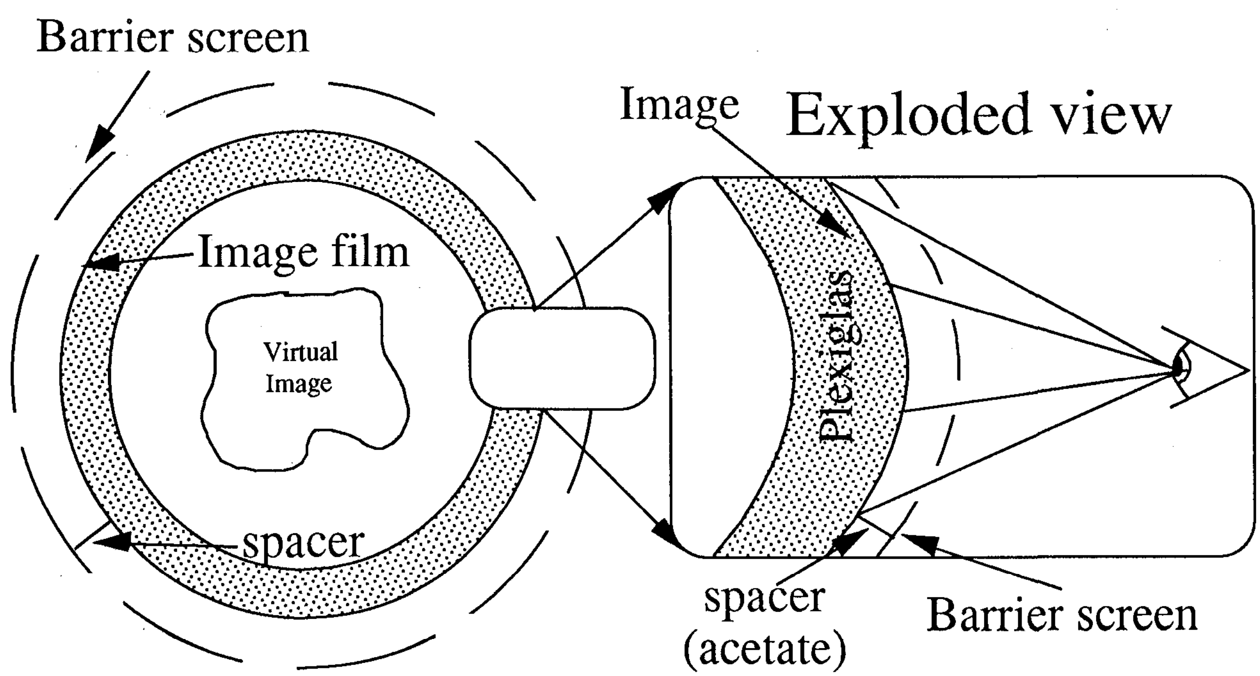
6.1 Description

Flat barrier-strip images, while impressive, are characterized by a limited viewing angle but good stereo. The viewer can only move about ten degrees and then the image repeats itself. While not a problem, as such, it is a limitation.

We are developing an alternate form which addresses this limitation, the *cylindrical barrier-strip autostereogram.* By cylinder, we refer to an outside view cylinder, where the image appears to float in the middle. The construction of this is essentially that of a flat autostereogram wrapped in a circle.

A Plexiglas tube (6" radius for our test) is placed around a light source (fluorescent bulbs) to provide a framework to work with. The image is wrapped around the cylinder. Around that we wrap sheets of acetate, usually between 0.020 and 0.060 inches total thickness. Finally, the barrier screen layer is wrapped around the acetate.

The end result of this process is an image which one can walk around, with a nearly 360 degree viewing angle possible. The image is seen in a window which is not as wide as the entire cylinder. The image repeats itself, in distorted form, to the left and right of the window.

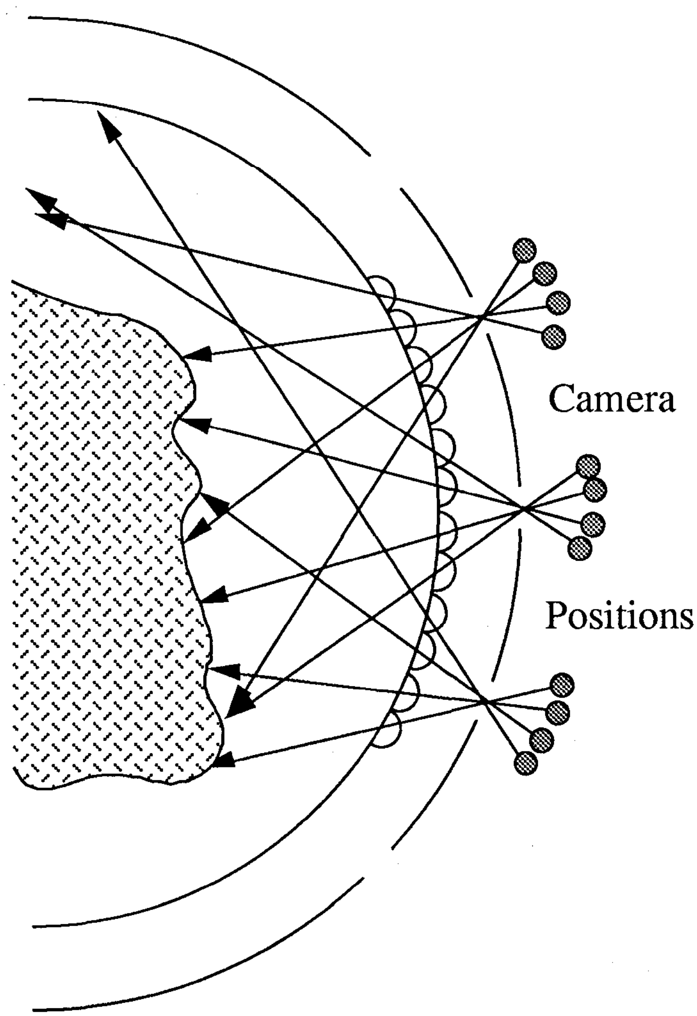


6.2 Computation

The equations used to compute the various views of an object would be very difficult (but not impossible) to apply to photographs of multiple view of real-time objects. We replace the off-axis perspective projection of the flat autostereogram with a *cylindrical perspective project.* Each one-pixel-wide vertical column in the image is computed from an entirely separate camera viewpoint. The virtual camera in the computer software is aligned to look through a slit in the barrier screen at the one-pixel column to be computed.

The process is complicated by the variations of the radii of the image and barrier screen. Since barrier screens are produced on the same scanner as images, their pitch has an integral relationship. However, when they are wrapped onto cylinders of different radii, the radial pitches become different. This problem is solved by finding the optimal slit for a given image column. Since we know the step angle between slits (ΔS), and we can find the angle to the current image column (θ), we simply find (round(θ / ΔS) * ΔS), which gives us the angle to the best slit.

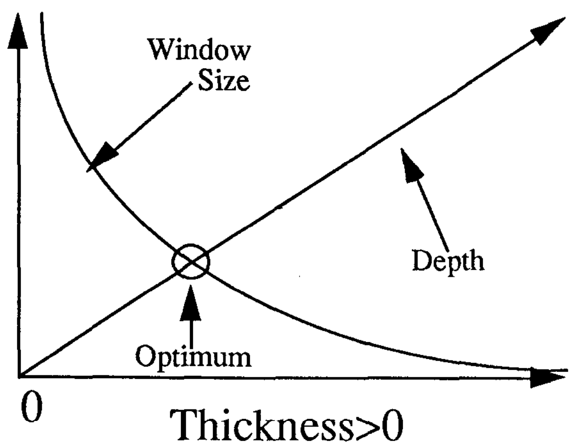
Another problem arises from the large viewing angle required to make a useful view window. Although this effect is insignificant in flat autostereograms, when one looks at a sharp angle through plastic, refraction results. This refraction requires a further degree of correction in software, since the refraction causes each image column to be viewed at a different angle (or through a different slit) than would otherwise be computed. When one knows the index of refraction for the spacer plastic, it can be put into the computation. As long as every column is computed from a viewpoint through the closest slit, taking into account the thickness and refractive index of the spacer plastic, the system automatically works.

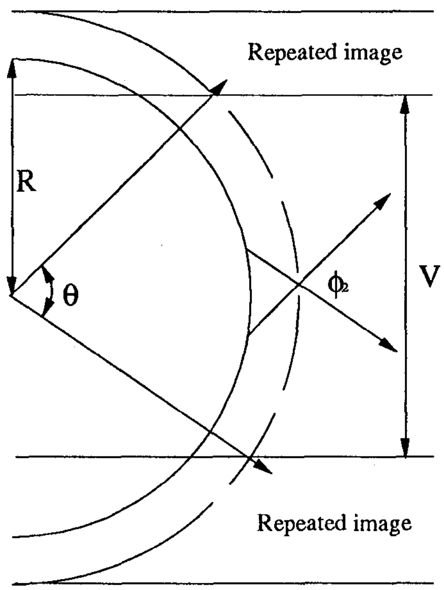


6.3 Tradeoffs

There are numerous tradeoffs in the cylindrical autostereogram system. These relate to four main variables, all of which interrelate.

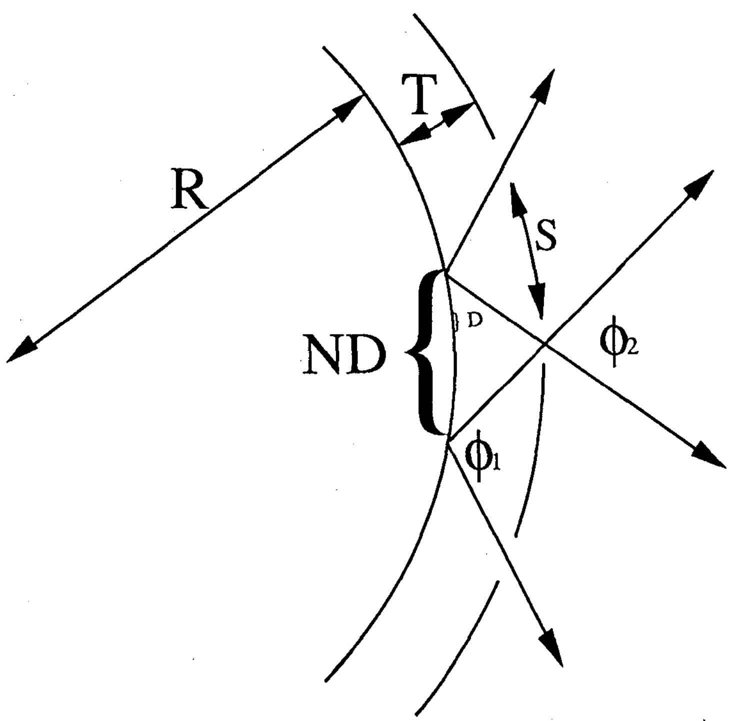
1) Number of images (N)
2) Thickness of plastic spacer (T)
3) Window size (V)
4) Quality of depth (Q)





$\theta = \phi_2$ for large view angles

$V = 2R\sin(\theta/2)$



R = Radius of cylinder
T = Thickness of spacer
N = Number of images/slit
ϕ_2 = Group angle
$Q = N/\phi_2$ = Images/unit angle
D = Width of column (1/400")
S = Distance between slits
V = size of view window

$\phi_1 \cong 2\arctan(S/2T)$

$\phi_2 \cong 2\arctan(ND/2T)$

$S \cong ND$, so $\phi_1 \cong \phi_2$

The number of images images per slit (N) is inversely proportional to resolution (1/S). Further, the thickness of the spacer (T) is proportional to the quality of depth (Q).

Let us make the size of the viewing window (V), radius (R), and column width (D, 1/400" for our scanner) all constant. This means that N/T is constant. Therefore, an increase in horizontal resolution must be accompanied by a decrease in the quality of depth.

Similarly, increasing the size of the view window must be accomplished by either decreasing thickness, which decreases quality of depth, or by increasing N, which lowers horizontal resolution.

We require a large group angle (much larger than for flat autostereograms), since the image repeats where the viewer's angle to the cylinder exceeds the group angle. This requirement puts severe conditions on the viewing angle versus resolution of the image. The spacer must be very thin, and the pitch of the barrier screen must be very coarse. At present, we are using roughly 13 lines per inch, compared to 45 or 31 in the flat system. This makes the image not only coarser, but darker. However, by making the opening in the slits twice the width of a single image line, we both increase the brightness and gain antialiasing (since each slit in the barrier screen is averaging at least two image lines).

The one immutable constant used in these calculations is D, the width of a column. This is based on the maximum resolution of the scanner. Scanners with higher resolution and lower cost will soon be available, thus allowing an increase in both horizontal resolution and window size with no loss of other variables.

6.4 Implementation

The computation method discussed is general purpose. It may be applied to other non-planar projections, such as interior-viewed cylinders (ones surrounding the viewer), or alcoves (cylindrical, parabolic, or any other geometry). It can also be used to produce intimate planar projections, which allow for very close viewing distances, or to match computed images to arbitrary pitch barrier screens or lenticular grids.

This method does, however, present some difficulties. With many existing commercial renderers, a system must be reinitialized and reloaded with data each time the camera is moved, which is each column of the image. This works out to over 15,000 repetitions for 360 degrees at a 6 inch radius. In one commercial raytracer, this results in a 10 to 30-times slowdown as compared to an equivalently sized planar PHSCologram.

However, a custom ray tracer has been written which optimally simulates the geometry of the cylindrical method. The algorithm can be parallelized for ray tracing, z-buffering, or any other image-space algorithm.

7. Conclusions

Our earlier research with computer-generated autostereograms has led us inexorably towards increased quality and lowered cost. Cibachrome film has proved superior to other methods as a final presentation medium for the highest quality images. Our desire for decreased cost has resulted in advances in the technique of mass production of both barrier-strip and lenticular imagery.

We also wanted to expand our capabilities. To this end, we developed methods for making larger images than previously possible, and have expanded the potential content of images by learning to combine and manipulate three-dimensional images.

Finally, our work with flat barrier-strip imagery inspired us to proceed to non-planar projections, developing a new computation method which is widely applicable to a range of related problems. Cylindrical barrier-strip imagery shows great potential as a new medium for presenting three-dimensional information, allowing a viewer to examine all sides of a three-dimensional object.

Our continuing research goals are to improve upon printing techniques, expand and perfect cylindrical projections, experiment with other non-planar projections, and use new, higher resolution output devices.

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