

Computer-generated barrier-strip autostereography

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Abstract

This paper discusses (1) the computer graphics transformations necessary to produce source images for barrier-strip autostereograms, and (2) current research to replace photographic processes with computational processes to combine different views into a stereogram. By connecting a computer to a high-resolution output scanner, computer-based images and digitized camera images can automatically be combined and printed on transparency film. Automating this process improves the visual quality of the autostereograms and expands the medium's commercial and artistic potential.

1. Introduction

As we enter the next decade, three-dimensional (3D) imaging will become more common than ever before. Humans are capable of simultaneously receiving two dissimilar images of the same object and perceiving depth. The projections for stereo viewing have not changed since Euclid's description in 280 A.D.; technologic and photographic advances are making it easier to produce the two images that stimulate the eye's binocular parallax and convergence cues.

1.1. A photographic history of 3D imaging

The first stereoscopic drawing technique was developed by Giovanni Battista della Porta around the year 1600. Although none of his drawings exist today, his technique involved drawing two precise pictures of an object observed from two different directions. For the next 200 years, other artists drew stereoscopic images, but the invention of photography and the development of stereoscopes in the 1800's overshadowed this technique.

The invention of the computer is causing a new revolution in 3D imaging to occur. The power and flexibility of computer graphic tools and techniques are enabling today's techno-artists to create stereoscopic scenes and, more importantly, to combine and record these images directly to film. The latter process, described in this paper, represents a new photographic technique — that uses a computer instead of a camera.

The history of photography has been dramatically affected by the tools available to, and developed by, the artists that use them. In 1976 the Royal Photographic Society published a series of charts that described the evolution of technology, and permitted a ready method for recognizing the historic place of particular images. The series included a chart of negative images and a chart of positive images.

Negative images were further categorized: (1) negative images on paper (plain and translucent) and (2) negative images on transparent material (glass and film). The Calotype (Talbotype) process (1840 - c.1855) uses negatives on paper; the Albumen print process (1848 - c.1885) is an example of negatives on glass; the cellulose nitrate film method (1889 - c.1939) is used to store negatives on film.

It seems reasonable that a third major category is now necessary: *stealth* negatives. From an art historical view, this paper describes a new technology where the negatives are actually information stored on digital media (such as floppy disks, magnetic tape, and so on). It seems fitting that this 1989 conference on Nonholographic True 3D Display Technologies coincides with the 150th anniversary of the birth of photography.

1.2. A technologic history of 3D imaging

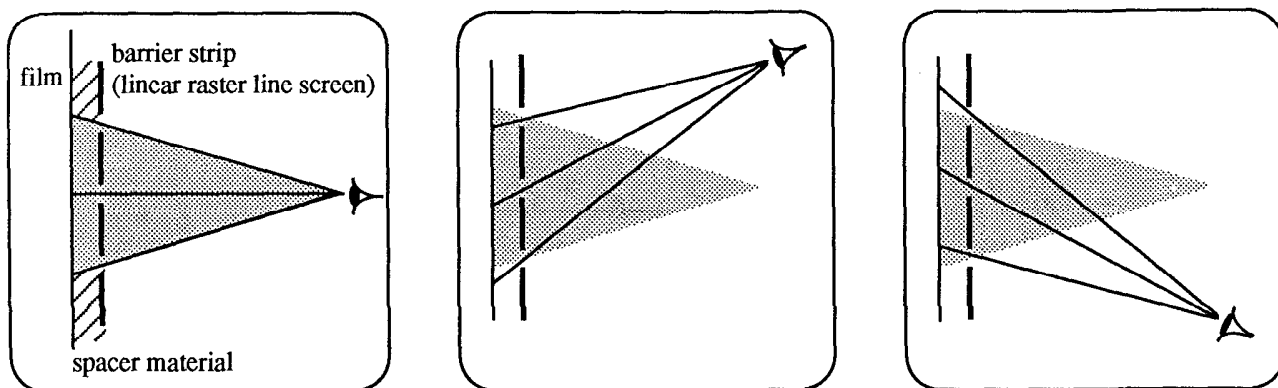
The stereoscope was developed in the 1800's, due to the efforts of Niepce, Wheatstone, Brewster and Holmes. Major achievements in and public awareness of 3D did not occur until the 1900's. Various stereocameras that produced binocular picture information were next developed and are still popular today, and related technologies evolved from Kennedy, Kanolt, Lippmann and Ives. The technologies being explored were the parallax barrier, chromolinoscope, panoramagram, and integral fly's-eye and lenticular photography. (Okoshi, 1976)

By the mid 1900's we had anaglyphic and polarized 3D movies. Cinerama and holography retained public interest, with work being done throughout the world in autostereographic television and the perfection of lenticular-sheet 3D pictures. Advancements to lenticular-sheet imaging were made by scientists Vanbenschoeten, Bonnet and Winnek, and by industries, including Eastman Kodak and Japan's Toppan and Dai-Nippon printing companies. (Okoshi, 1976)

2. Scene reconstruction using barrier-strip camera-combining methods

2.1. Description of the barrier-strip method

Barrier-strip technology, which uses a line screen, is the pinhole equivalent of the lenticular system, which is based on cylindrical lenses. In the former, the eye sees images through slits in a line screen; in the latter, the eye sees images refracted through the center of the curvature of a series of lenses. All methodologies described in this paper apply to lenticular as well as barrier-strip systems, except for the automatic generation of the barrier strip itself (described in section 3).

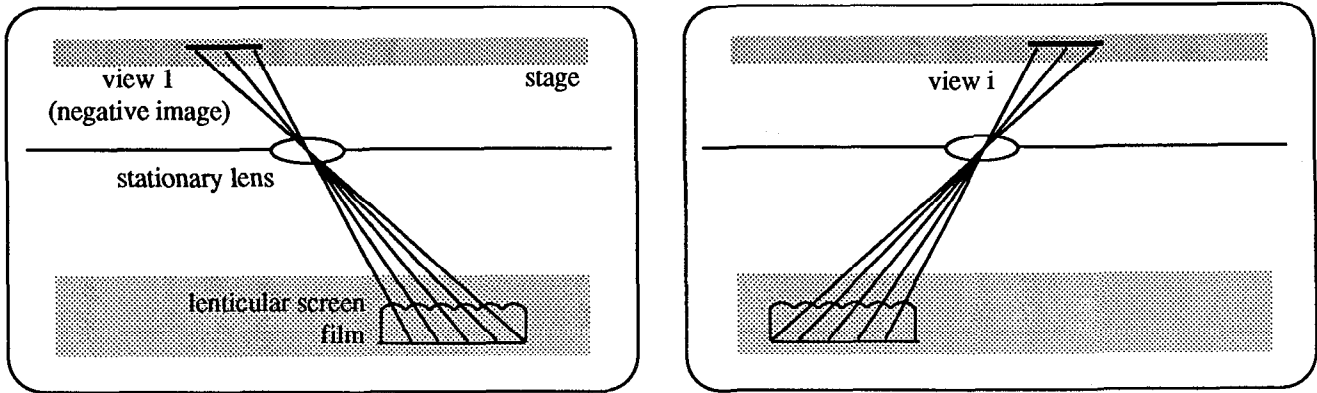


The *barrier strip method* allows viewing of n different views of an object. This process cuts each view into vertical columns, interleaves the columns, and positions them behind the slits of a barrier strip. The position of the eye determines what view the observer sees.

2.2. Types of camera projection systems

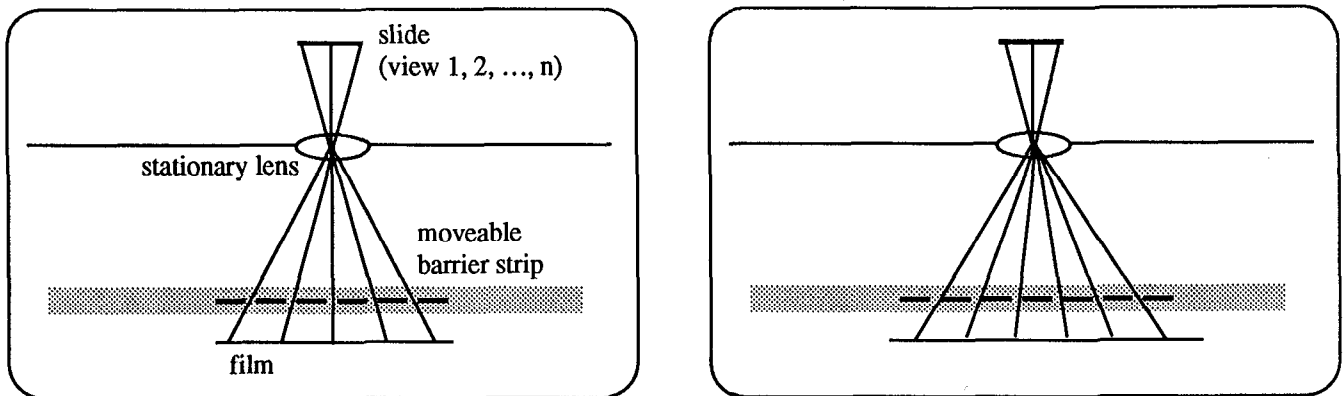
Most 3D photographers today use Bonnet-style cameras, which have barrier-strip or lenticular screens in the back of the camera. In a one-step *dedicated process*, they photograph a scene; the lenticulation is immediately put into the film during processing. Images have a specific *spatial frequency* (also: *pitch, lines per inch*). These rulings can only be magnified proportionally; images that are reduced or magnified may appear too fine or too coarse.

A two-step *combining process* expands the photographer's flexibility to magnify or crop images. For example, the projector developed by Bernard Jéquier is a combining camera. (Jéquier, 1983)

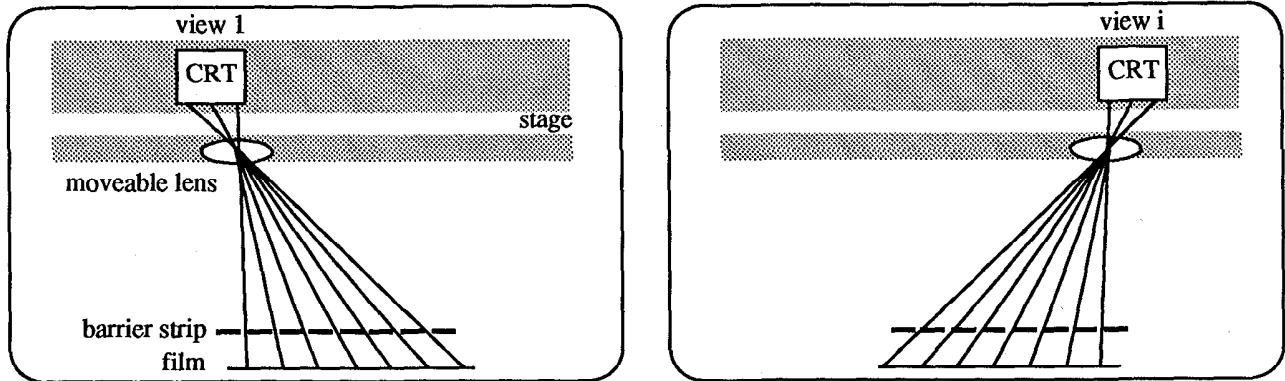


Jéquier's projection system uses n different negatives of an object scene, previously photographed on negative film from n different positions. Each negative is inserted, in sequence, in a stage (slider) that moves left and right; the film and lenticular screen move accordingly. The process splits an image into vertical columns, interleaves them and records them on film.

The following two methods are implemented at (Art)ⁿ Laboratory to produce autostereographic phscologramsTM (pronounced skol•o•grams). For each of these processes, scenes and appropriate views are first created and stored on slides, videotape, or in files in a computer's memory. Second, we combine, or interleave, the n different views of the scene photographically onto film.



The Cunnally projection system has a moveable barrier strip; the rest of the system remains stationary. The barrier strip moves $1/n$ -th the distance between lines for each slide. The film is placed on a vacuum-backed table; the barrier strip is mounted in a frame which is attached to the table with spring-loaded pins. A micrometer is used to control the movement of the barrier strip, up to $1/1000$ -th of an inch.



The *Illusion projection system* photographs n different scenes off a CRT screen. The lens and the CRT monitor move n proportional distances left and right; the film and barrier strip remain fixed. This process splits each image into vertical columns, interleaves them, and records them on film.

2.3. Using camera-combining methods on computer-generated scenes

Computer-generated images

Computer graphics environments are graphical representations of mathematical equations. Once a graphical model is developed, we render it (add color, lighting, textures, and so on) and determine the appropriate viewing angle and depth information. To determine the viewing angle, we interactively rotate the scene on a CRT monitor until we find an angle that is both mathematically intriguing and aesthetically pleasing, and then store the resulting image for subsequent photographing. The *viewing angle* is what an observer sees standing directly in front of a phscologram.

To give the illusion of depth, we mathematically do an off-axis perspective projection of the scene both left and right about its *center of depth*, storing the different offsets in image files on the computer. The degree of off-axis projection determines the *amount of depth* an observer sees when viewing a phscologram.

The images are photographed, combined and recorded on transparency film using the Illusion projection system. The processed and printed film is inserted into a light box for viewing.

Video input methods

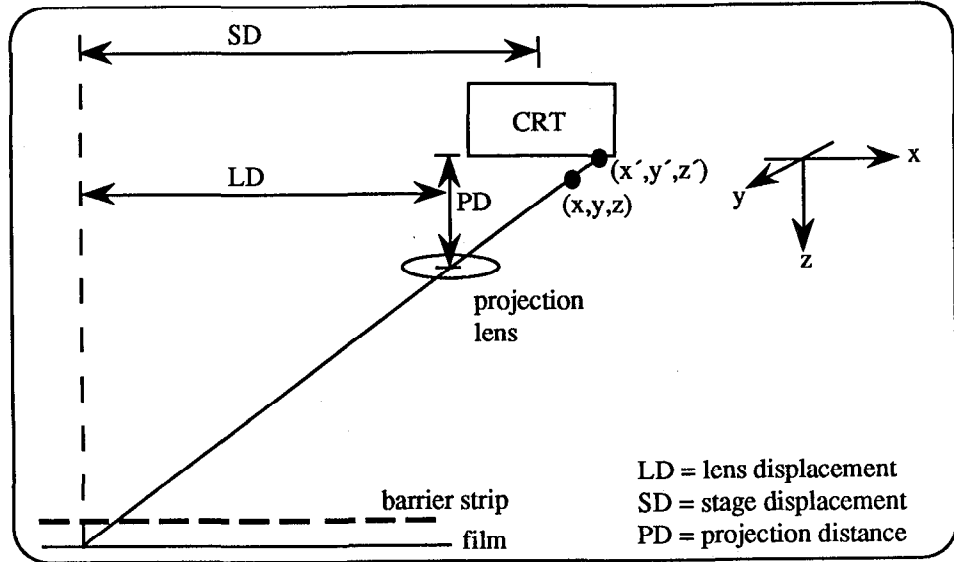
We work primarily with images on CRT's; hence, these images can be computer generated, or can come from the outside world using video cameras. We translate (or truck) a video camera in front of a scene and record a huge number of perspective projections (30 frames per second) using optical computations (the lens of the video camera).

The tape is put into a computer-controlled video tape player and a sequence of frames separated in time is automatically grabbed (or digitized) and stored in the computer's memory. The distance between frames determines the amount of depth.

Once the images are in the computer, the images are translated so a particular point common to each frame is in registration. This point becomes the center of depth of the phscologram. This process provides the n different off-axis perspective projections necessary for the phscologram.

The projection geometry for making phscolograms

Consider a point in space (x,y,z) . We need to calculate a point on the surface of the monitor (x',y',z') that, when photographed, will have the same projection on the autostereogram. To do this calculation, we use off-axis perspective projection.



Calculate the relative lens displacement: $LSD = (SD - LD)$

By proportional triangles, we know: $\frac{x' + LSD}{PD} = \frac{x + LSD}{PD - z}$

Therefore: $x' = \frac{PD(x + LSD)}{PD - z} - LSD$ (1a)

x' is equivalent to a displacement in x of LSD , followed by a standard perspective projection, followed by a displacement in x of $-LSD$. This is further equivalent to the following, which is a shear of x by z , of the amount LSD/PD .

$$x' = \frac{PD(x + (LSD/PD) * z)}{PD - z} \quad (1b)$$

y' is the standard perspective projection: $y' = \frac{PD * y}{PD - z}$ (2)

$$z' = 0 \quad (3)$$

Note: Because off-axis perspective projection is not available and the standard perspective projection is difficult to modify in most commercial rendering software packages, we recommend multiplying the image and light source by a shear transformation matrix and then doing a standard perspective projection.

Sample code

Here is a sample code fragment illustrating shear to do off-axis projection:

```
.*****
. RT/1 code fragment
. USES SHEAR TO DO OFF-AXIS PROJECTION FOR +/- 1 UNIT SYSTEM
. TO PRODUCE PHSCOLOGRAM FORMAT
.*****
. Note on RT/1 ";" is a statement delimiter
.           "." at the beginning of a logical line is a COMMENT
.
. n          = number of frames, or views (n is an odd number)
. unitsperinch = vertical units per inch on monitor
. lenzdisp    = lens displacement in inches per frame
. stagedisp   = stage displacement in inches per frame
. lenztoobj   = lens to object distance
. lenztofilm  = lens to film distance (not used)
.
PRINT "FRAME NUMBER 1 to n"
INPUT frame
frame=frame-(n/2);      .Converts from numbers 1 to n to
                        .frame numbers -(n/2) to +(n/2)
d2=lenztoobj*unitsperinch;
                        .Perspective view distance in inches
sd=frame*(stagedisp-lenzdisp)*unitsperinch;
                        .Off-axis distance in inches

SETCUBE "CUBE",400,400,400; HOME;
                        .Creates object to be displayed
SHEAR "Z","X", sd/d2;  .Shear along Z by X
PDISP lenztoobj*unitsperinch
                        .Does perspective display with
                        .view distance = lenztoobj * unitsperinch
```

Experiences with systems

By using a combination of video input and computer-generated images — rendered on a large range of computers, from personal computers to supercomputers — (Art)[®] Laboratory is able to create barrier-strip autostereograms of importance to the scientific and art worlds. Other research laboratories, corporations and universities have been collaborating with (Art)[®]; their researchers have successfully used a sample program similar to the one above to provide us with the images necessary to produce phscolograms.

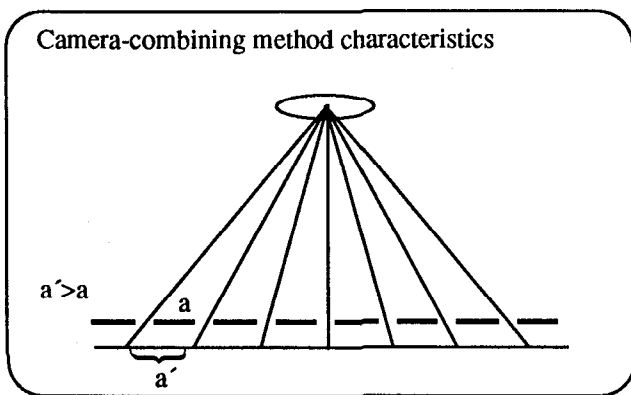
The inaccuracies and inflexibilities associated with the camera-combining method have, however, been a constant source of problems. Cameras are subject to geometric changes with temperature and humidity, exposure problems and color balance problems. The process itself is expensive; slow because of many processing steps; requires a large physical facility for the camera, darkroom, and so on; and, depends upon outside assistance for photoprocessing. Because much of our work is already computer-based, we started to investigate using the computer to do the combining, thereby eliminating the

3. Scene reconstruction using barrier-strip computer-combining methods

Since the camera-combining process interleaves columns of different images, it is possible to generate a barrier-strip autostereogram using the computer to sort on the different images and record directly to film. We are simply simulating the camera's combining method with a computer.

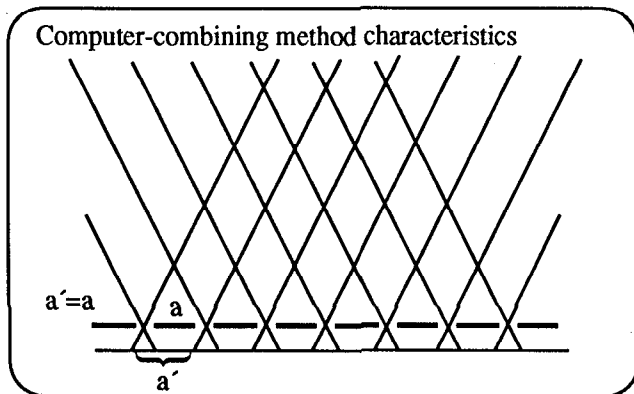
3.1. Mathematical transformations for computer combining

When using the camera-combining method for making autostereograms, we modeled the geometry of the projection system to computer generate the different views of a scene. Using the computer-combining technique, there is no camera-combining system to model; hence, we had to look at the autostereogram itself and work backwards to derive the mathematics. For reasons described below, the computer-combining method uses a barrier strip that has the same pitch as the image material, unlike the camera-combining method that uses a perspective projection.



The *camera-combining method* uses a projection lens to project a diverging light beam. The image is refracted in a fan-like fashion.

The spatial frequency (pitch) of the lines on the barrier strip is slightly higher than the frequency of the columns of images on the film because of the projection.

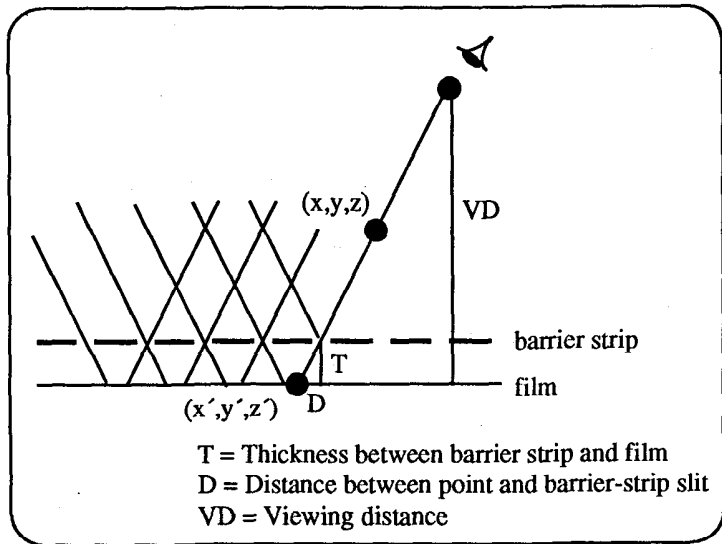


The *computer-combining method* projects parallel light beams.

The spatial frequency of the barrier strip is exactly the same as the frequency of the columns of images projected on the film.

Equations for image rendering

If we want a point to be viewed at position (x,y,z) in front of the image plane, we need to calculate the position (x',y',z') on the film plate that will make that projection.



We first do a shear of z by x by a factor of D/T . This equation is the same as equation 1b, except that there is no perspective projection. The barrier strip itself does a perspective projection for the viewer at distance VD in the horizontal (x) direction.

$$x' = x + (D/T) * z \quad (4)$$

In the vertical (y) direction, we perform a standard perspective projection from viewing distance VD (see equation 2):

$$y' = \frac{VD * y}{VD - z} \quad (5)$$

$$z' = 0 \quad (6)$$

Algorithm to combine images

The computational process of combining n different frames of an image into a single autostereogram is straightforward. We first determine the following, and compute accordingly.

- The size (height/width) of the film we are writing
- The resolution of the output device
- The number of views of the image being encoded

The images are then interleaved using an automatic sorting method and written out to film. Image 1, column 1 is placed next to image 2, column 1, followed by image 3, column 1, and so on.

column	1	1	1	...	1	2	2	2	...	2
image	1	2	3	...	n	1	2	3	...	n

The barrier strip is also written out using the same method used to write out the columns. We write out 1 or 2 clear lines, followed by $n-1$ or $n-2$ black lines, respectively.

3.2. Experiences recording autostereograms directly to film

We are currently exploring two types of output devices. Sandin, Sandor and Cunnally are using high-accuracy output scanners associated with the graphic-art prepress industry. Resch is exploring low-cost high-resolution laser writers designed for the desktop publishing industry.

Desktop publishing: Laser writer experiences

To produce an autostereogram, we design and render n different views of a scene on our computer system using Clockworks, software developed at Rensselaer. The output of Clockworks is converted to hexadecimal ASCII (text) files; each character in a text file corresponds to a pixel in the original image. A "C" program is used to interleave the *characters*, or columns of images. The resulting interleaved image (still a text file) is combined with a PostScript™ header that specifies how the files are to be processed. The files are stored on floppy disks, which are sent to a Linotronic L300 typesetter for processing. The barrier strip is generated in a similar manner.

The Linotronics is a monochrome (black-and-white) device, and has a maximum resolution of 2540 dots per inch; we are currently working at 1270 resolution. In order to produce images with grey values, the PostScript file converts each character (pixel) in the text file to an array of 4 x 4 dots; PostScript maps each character into a particular grey value. Images are printed on transparency material.

Because of the high degree of registration of these devices, we can put the barrier strip on one side of a spacer, the printed image on the other, align the two pictures on a table top and snap them into a standard picture frame. This frame is then be inserted into a light box for viewing.

High-resolution film recorder experiences

Current results are being obtained using a Crosfield scanner designed to do separations with dot screens for large-scale, high-quality printing. These devices have an internal accuracy on the order of .0005 inches.

This machine was selected to circumvent several problems we found with most common computer output devices; notably, the latter do not have the necessary resolution and precision needed to produce autostereograms. The camera-combining method typically projects a few hundred or a few thousand image columns per inch, with accuracies between .001 to .0001 of an inch. The spatial quantization imposed by computer output devices causes moiré patterns (sampling errors) when the barrier strip and the film are aligned.

To produce a phscologram, we render and combine n different views of a scene on our computer system, write the image file and corresponding barrier strip to a 9-track magnetic tape, and then input the data on the tape to the scanner. The data format used is compatible with the Crosfield archiving procedure.

Although there is a way to manipulate the scanner's line-screen dot generator, we would have to generate too large a quantity of data; therefore, we decided to write tapes in the scanner's standard format using standard procedures. The accuracy is good enough in this mode, but the spatial frequency of the dots generated by the scanner still has the potential to create moirés from the interference of the resulting barrier strip with the interleaved picture; that is, the number of dots per inch on the scanner is not necessarily coincident with the number of pixels per inch in the file.

Also, dots are laid down at different angles and varying sizes for different colors, the intersections of which form a rosette pattern. The angles and spacing of the dots have been carefully chosen to minimize moirés with one another. We, however, are producing two images (a barrier strip and an interleaved image) we want coincident, which is effectively sampling the dot pattern again. This has the potential of causing very disturbing moving dot and line patterns in the final image.

We found we could correct this moiré problem (1) by using the half-line mode (instead of the dot generator) and (2) by aligning the columns of images and the barrier strip parallel with the lines produced by the yellow channel. Half-line mode draws single lines of varying width at the same angle the dot generator puts dots; hence, we are sampling or quantizing in one

dimension instead to two. Different colors have different drawing angles associated with them; we selected the yellow channel, which draws vertically, so we could align all our columns vertically.

From the scanner we get four orthographic films (high contrast, black-and-white) for our interleaved image, one each for yellow, magenta, cyan and black. We also produce one film of the barrier strip, from the half-line yellow channel.

In the prepress industry, these films would eventually be transferred to plates and put on printing presses. Since the prepress and printing processes are somewhat costly, the prepress industry has several proofing methods to manually produce test prints, to make sure the information on the films is correct. We do a Cromolin™ proof on our films. We put the resulting print of the interleaved image on one side of spacer material, the barrier strip on the other side, and mount the finished work in a light box for viewing.

4. Conclusions

Our research on computer combining was motivated by the problems and costs associated with camera technology, the desire to bring down the overall cost of production, and an interest in mass producing 3D hard copy. We investigated using graphic-art scanners and desktop laser writers because of their high resolution and accuracy, and because they are standard equipment in the prepress and desktop publishing industries, with standard procedures, tape formats, and so on. We also determined we could produce images of clearer depth and potentially better color control on prepress scanners than would be possible using camera-combining techniques.

While prepress costs are expensive, they have an extremely high level of quality and have the potential of becoming more economical. When mass producing phscolograms, the costs certainly decrease. It is possible to take the resulting films, make plates and print the images on transparency material. We also want to investigate printing the image information on one side of a thin piece of plastic and the barrier strip on the other, to eliminate the manual process of aligning and adhering the interleaved image and barrier strip to spacer material.

The desktop publishing method is fast (approximately 15 minutes to output information on a floppy), economical (\$3 - \$40) and easily available. The method provides an alternative to the more expensive scanners for on-demand 3D visualization.

The visual impact of displaying 3D information in 3D is gaining immediate acceptance in the scientific and art worlds, and we see this type of 3D presentation medium becoming as important as slides, videotape and film for communicating ideas, insights and discoveries. Scientists are interested in this presentation method to display complex multi-dimensional data more clearly; artists are using this technology to create works of aesthetic and social impact. Our collaborations with industry, government and academia give testimony to these statements.

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Phscologram is a registered trademark of (Art)[®] Laboratory, Chicago, Illinois. PostScript is a registered trademark of Adobe Systems Incorporated, Palo Alto, California. Cromolin is a registered trademark of Du Pont, Wilmington, Delaware.

(Art)[®], in collaboration with the Electronic Visualization Laboratory, has been producing computer-generated autostereograms since 1984.

6. Bibliography

F.E. Ives, U.S. Patent, 725,567 (1903).

F.E. Ives, U.S. Patent, 666,424 (1091).

H.E. Ives, "The Chrominoscope Revived," *J. Opt. Soc. Amer.* 20, pp. 343-353 (June 1930)

H.E. Ives, "A Camera for Making Parallax Panoramagrams," *J. Opt. Soc. Amer.* 17, pp. 435-439 (Dec. 1928)

B. Jéquier, "Some simple means of realizing 3D images with standard material in diverse fields of medicine, industry and research," *Proceedings of the SPIE No. 402/37*, Geneva (1983).

S.H. Kaplan, "Theory of Parallax Barriers," *J. SMPTE* 59, No. 7, pp. 11-21 (July 1952)

T. Okoshi, *Three-Dimensional Imaging Techniques*, Academic Press, New York (1976)