Full-color 3-D Prints and Transparencies*

J. J. Scarpetti,† P. M. DuBois,† R. M. Friedhoff,† and V. K. Walworth‡

The Rowland Institute for Science, Cambridge, MA 02142

We have put into practical form one of Edwin Land's early inventions, the stereoscopic Vectograph image. We have reinterpreted the concept to produce digital 3-D hardcopy conveniently from both photographic and digital 3-D records. Digital 3-D images may be produced directly by digital cameras, by computers and workstations, and by various instrumental outputs or they may be acquired by scanning and digitizing photographic image pairs. Digital 3-D polarizing images are printed conveniently with an ink-jet printer. To produce full-color 3-D hardcopy on standard ink-jet printers we have formulated special inks and substrates. Our technique unites two very significant growing technologies: ink-jet printing and 3-D imaging.

Journal of Imaging Science and Technology 42: 307–310 (1998)

Introduction

The most commonly used method of 3-D presentation comprises encoding left- and right-eye images in terms of polarization by mounting oppositely oriented polarizing filters over the lenses of paired projectors and superimposing the left- and right-eye images on the screen, as shown in Fig. 1. To preserve the polarization, the screen used must have a metallic, nondepolarizing surface. Suitable aluminum screens are commercially available. Observers view the composite image through 3-D polarizing glasses. Under these circumstances each eye sees only the assigned image and the observer perceives the composite as a single three-dimensional image. This method is effective, but it is difficult to achieve correct and consistent stereoscopic registration and alignment without specialized precision equipment.

In 1940 Edwin Land introduced the Vectograph concept.[1] Instead of using polarizing filters to encode paired images, he used images that were themselves polarizers. He printed the respective left- and right-eye images on opposite sides of a single transparent support, as indicated in Fig. 2, so that once the two images had been properly registered and printed, they could not be misaligned.

The earliest Vectograph images were in black and white, and they were formed by staining preregistered paired gelatin relief images with an iodine ink and transferring that ink to oppositely oriented polyvinyl alcohol (PVA) layers laminated to opposite surfaces of a transparent film base.[§] In each image area the effective density is directly related to the amount of iodine transferred to the PVA and thus to the degree of polarization.

The chemistry of this Vectograph imaging process resembles that used in the production of sheet polarizers such as the Polaroid H-sheet. In each case the substrate is a PVA sheet that has been heated and stretched to orient the polymeric molecules, then laminated to a support and stained with an iodine ink. Such polarizers are defined as dichroic polarizers. Iodine may be described as a dichroic stain, and dyes that form spectrally selective dichroic polarizers are described as dichroic dyes.[2]

In 1953 Land showed three-color Vectograph images that had been formed by successively transferring cyan,

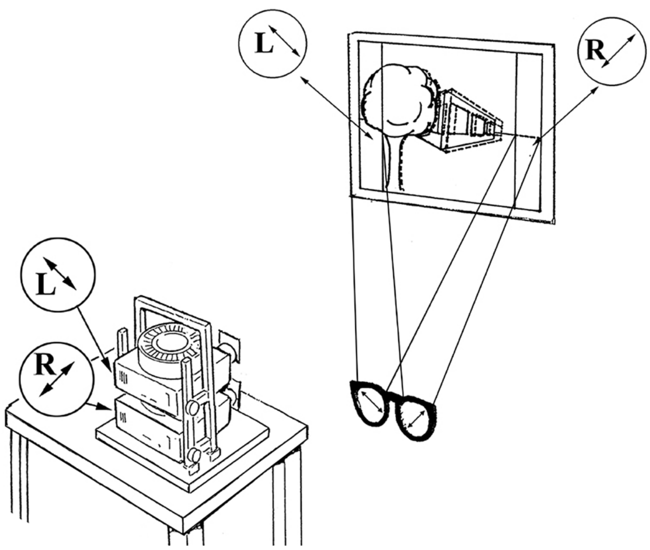

Figure 1. 3-D projection display with two projectors.

Original manuscript received November 10, 1997

* Presented in part at the IS&T 50th Annual Conference, Cambridge, MA, 18–23, 1997.

† IS&T Member

‡ IS&T Fellow

§ The black-and-white Vectograph process was used extensively for both military and industrial imaging during World War II. For many years Stereo Optical Co., Chicago, IL, has been producing black-and-white Vectograph prints for use by ophthalmologists in binocular vision testing and training.

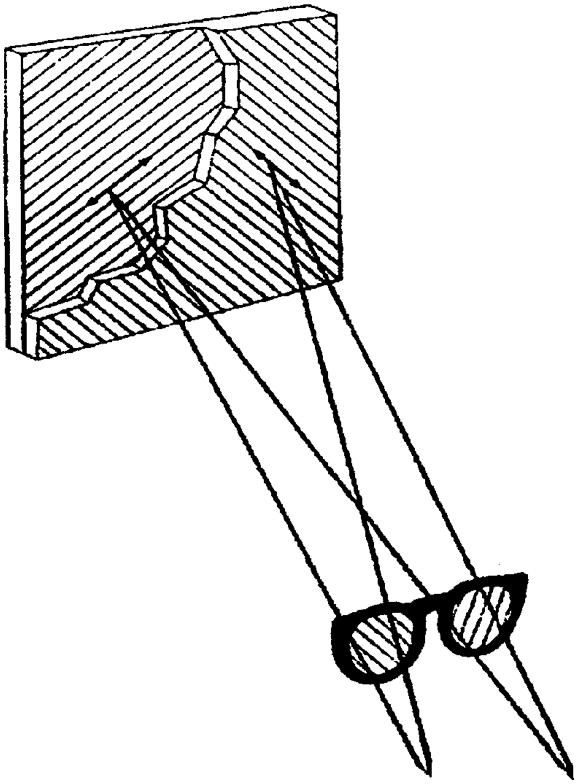

Figure 2. The Vectograph concept, using paired, oppositely oriented polarizing images.

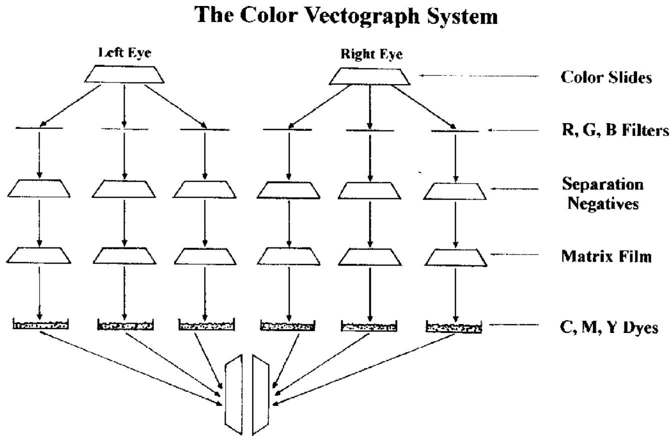

Figure 3. Color Vectograph image printing by dye-transfer process.

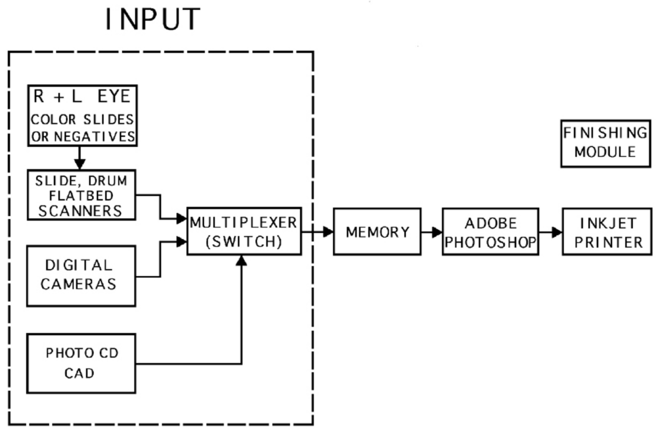

Figure 4. Flow diagram illustrating the preparation of digitized stereoscopic polarizing images. The principal steps are: (1) the preparation of a digitized left–right image pair, (2) storage of the two images as a left–right image file, (3) paste-layering, using Adobe Photoshop. Following adjustment of contrast and color, suitable cropping, and stereo registration, the two images are printed sequentially, one on each surface of the two-sided sheet.

magenta, and yellow dichroic dye images from paired gelatin relief images.¶ The color Vectograph printing process required for each 3-D image a set of six flawless, perfectly registered matrices, as indicated in Fig. 3. The process produced excellent stereoscopic color prints and transparencies and even experimental 3-D motion pictures. However, preparation was difficult, time-consuming, and costly, and these factors precluded widespread utilization of the process.

In recent years 3-D computer technology has dramatically influenced scientific, engineering, and medical imaging. For example, molecules, airplanes, oil rigs, and buildings are now designed or investigated using 3-D computers, often with real-time stereoscopic renditions displayed on monitors. Until now, however, there has been no convenient form of hardcopy for these 3-D display images.

The purpose of our investigation has been to develop a greatly simplified process for generating full-color 3-D prints and transparencies, using contemporary ink-jet printing technology with dichroic inks and specially constructed substrates. New materials and techniques make it practical to use ink-jet technology for printing full-color 3-D hardcopy images.[3]

Materials and Methods

Preparation of 3-D Digital Image Pairs. Figure 4 details the various paths from initial image acquisition to the finished stereo image. If the initial stereo images are conventional photographic negatives or positive transparencies, the images are first scanned and digitized. Image pairs from digital cameras, CAD images, and digital images based on various instrumental data are used directly. In addition to using an array of external sources, we can import digital 3-D images electronically from remote instruments and computers.

The paired left- and right-eye digital images are transferred to Adobe Photoshop or a comparable program. We adjust the contrast and color balance of each image, then register the pair stereoscopically, as illustrated by the two upper images in Fig. 5. Each of the two images is "paste-layered" into a new canvas, in which the dimensions match the dimensions of the printing medium, commonly 8.5 × 11″ or 8.5 × 14″. We then select the right-eye image, reduce its transparency to 50%, and move the image into stereoscopic alignment with the left-eye image, superimposing precisely the points that are to lie in the plane of the stereoscopic "window," i.e., the plane of the screen or frame, as shown in the lower left panel of Fig. 5. Finally, we restore full density and reverse the right-eye image right to left (Fig. 5, lower right panel), so that when the two images are printed face to face both images will again have the same left–right orientation.

Image Dyes. Figure 6 shows the structure of a typical dichroic azo dye suitable for forming polarizing images

¶ Presentation by E. H. Land at the 38th Annual Meeting of the Optical Society of America, Rochester, NY, 1953.

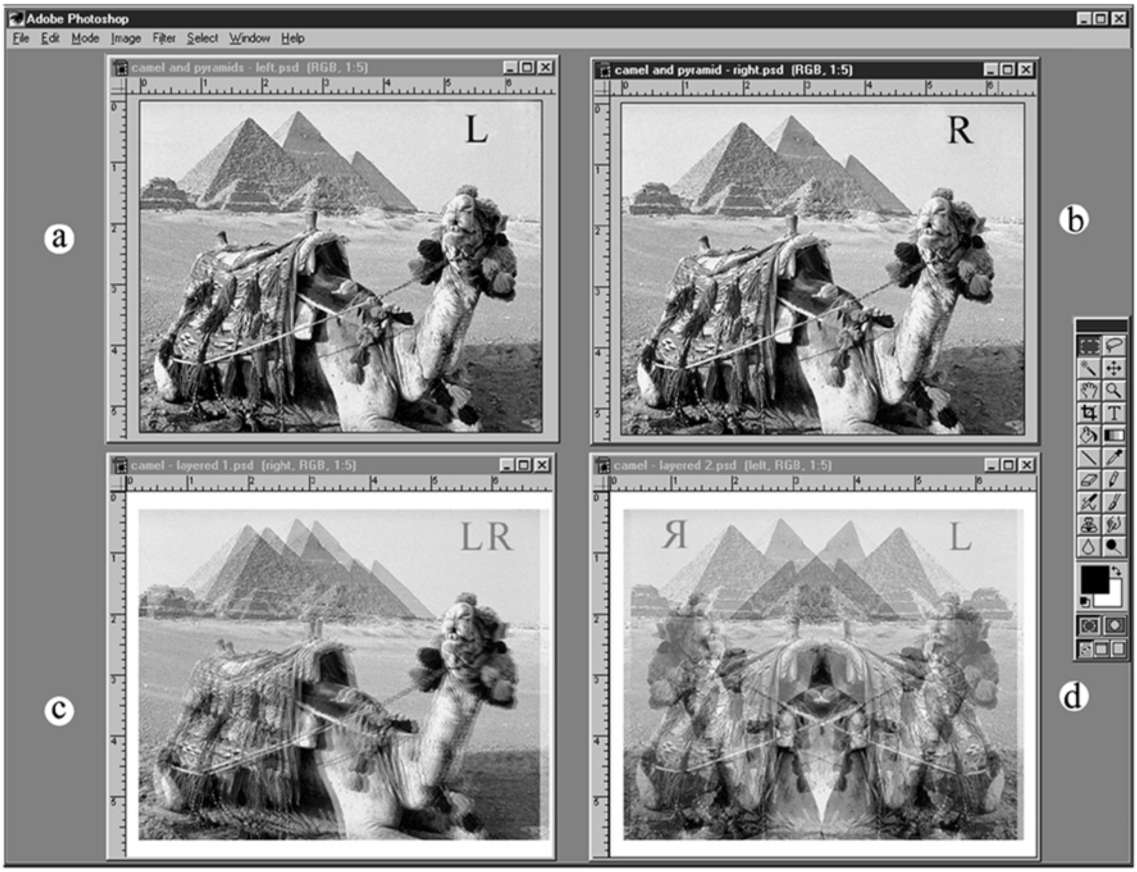

Figure 5. Monitor screen views showing the steps in stereoscopic registration of image pair.

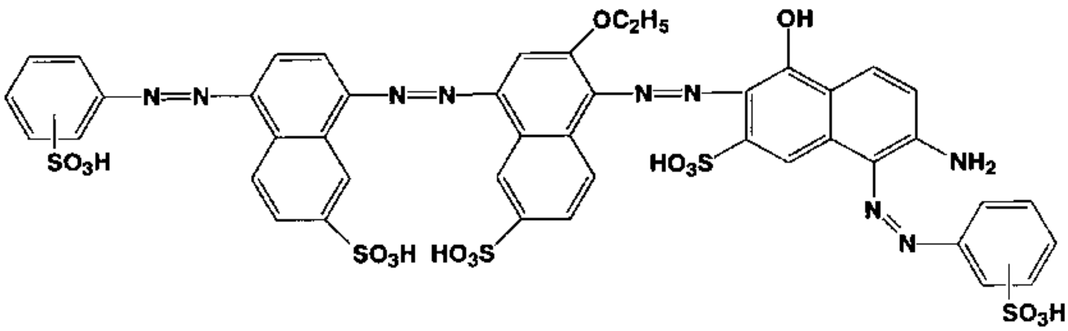

Figure 6. A typical dichroic image dye, Direct Green 27.

upon imbibition into an oriented PVA layer. The dye shown is Direct Green 27, which we use in the cyan ink.[4] The polyazo dye molecule is sufficiently flexible to align readily with oriented molecules of PVA to form an efficient dichroic polarizer. The sulfonic acid groups confer high solubility in aqueous solution, providing mobility of the dye within water-permeable polymeric layers. For our application the dyes are carefully purified and formulated into dichroic inks that perform well in standard ink-jet cartridges.

Sheet Material. We print the paired images on the two surfaces of a multilayer sheet, as represented in Fig. 7. The film base is a nondepolarizing transparent support of cellulose triacetate or cellulose acetate butyrate. An image-receiving layer of stretched PVA is laminated to each surface of the film base, with the stretch axes of the two PVA layers oriented at 90° to one another and at 45° to the edge of the sheet (Polaroid Corporation, Cambridge, MA). A thin metering layer of a nonoriented ink-permeable polymer, such as carboxymethyl cellulose, overlies the surface of each of the PVA layers, as indicated in Fig. 7.

Printing Equipment. Desktop ink-jet printers are characterized as drop-on-demand printers. The printhead comprises a bank of ink cartridges, one for each of three subtractive color inks and in most cases one for black ink as well. As the printhead moves rapidly across a sheet of paper or transparent base, microscopic nozzles eject ink onto the sheet. In certain drop-on-demand printers, such as those provided by Epson, electronic signals actuate piezoelectric diaphragms within the head to force the imagewise ejection of droplets. In bubble-jet systems, such as the Hewlett-Packard (HP) and Canon printers, heat-

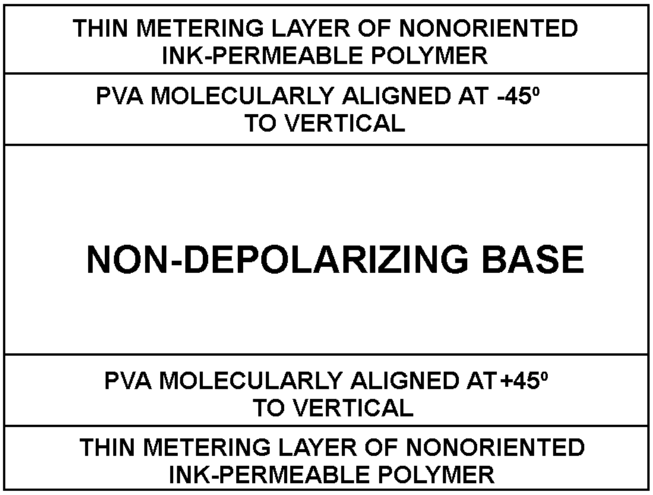

Figure 7. Schematic drawing of sheet structure.

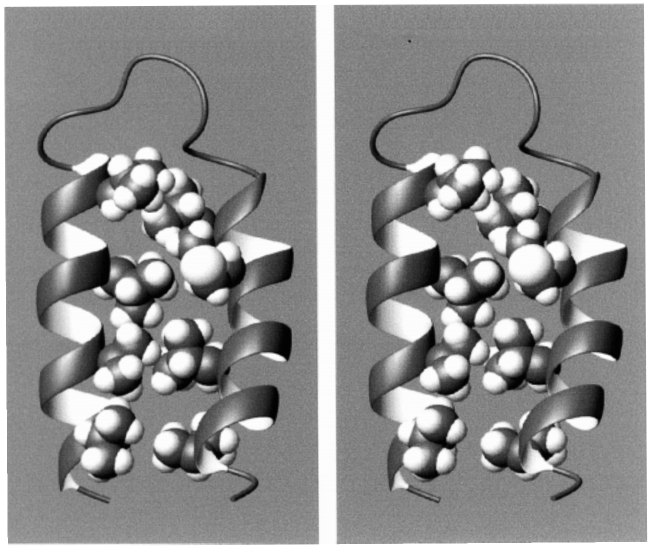

Figure 8. Molecular structure of α-t-α, a 35-residue peptide with a helical hairpin conformation in solution.[5] Left, left-eye image; right, right-eye image.

ing elements create bubbles that expand to force out the ink droplets.

Most of our images to date have been produced on HP printers, including Models 500C, 550C, 850C, and 820. We are also printing images on an Epson Stylus 800 printer. In each case the image resolution is determined by the resolution of the printer. The Hewlett-Packard printers are rated at 300 dpi and the Epson at 1440 dpi. To print the 3-D images, we insert standard ink-jet cartridges filled with dichroic inks into otherwise unmodified ink-jet printers. To make a transparency with the HP printer we select the media setting "transparency" and we set the intensity at "normal" to "darkest." To make a reflection print we select "glossy" as the media setting and choose "lighter" to "normal" ink intensity. We print the left-eye image on one surface of the sheet and the right-eye image on the opposite surface.

Finishing Stage. After transfer of the images to the oriented PVA layers has taken place, the metering layers are removed. Transparencies are mounted for viewing by overhead projection or for direct viewing on a light box. Images prepared for viewing as reflection prints are laminated to reflective aluminized backing sheets.

Results

We have used a variety of stereoscopic images in the course of our development work. These images represent many applications, including molecular modeling, microscopy, data visualization, entertainment, and pictorial photography. The 3-D image pair used in Fig. 5 was taken from a Photo CD file. Several of the images shown during the presentation of this paper originated as computer-generated or instrument-generated stereoscopic data. For example, a model of a complex protein molecule was produced from its molecular coordinates, using the program MOLMOL in a Silicon Graphics workstation.[5,6] The image information was saved as a TIFF file and transferred to a PowerMac in our laboratory via FTP, using NCSA TelNet. Fig. 8 illustrates the image as a side-by-side stereo pair.

The 3-D transparencies produced in desktop equipment are convenient hardcopy of size and quality suitable for projection in a standard overhead projector onto an aluminum screen or for direct viewing by transmitted light. In most situations the observers wear conventional linearly polarized viewers. The same images may be projected directly through an overlaid quarter-wave retarder for observation with circularly polarized viewers. The transparencies may also be viewed without glasses, using tabletop autostereoscopic display apparatus.

Although all of the prints and transparencies produced so far have been printed on desktop equipment, we are exploring the applicability of larger format drop-on-demand printers and continuous-flow ink-jet printers.

Summary and Conclusions

We have developed a 3-D imaging system that should be compatible with many of the color ink-jet printers now in use. All indicators suggest that ink-jet printing will continue to be a leading technology for producing digital hardcopy of high quality. Advances in resolution, image quality, speed, and convenience are occurring rapidly in the ink-jet industry, and these advances will contribute to the utility of our process. The increasing use of 3-D information in many fields makes it desirable to have ready access to high-quality 3-D hardcopy. We believe that our technology offers new opportunities for modern stereoscopic imaging.

Acknowledgments. We thank David Burder for the use of several of his 3-D images, including the pair used in Fig. 5. We also thank John Osterhout for the image of the molecule shown in Fig. 8.

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