Official Monthly Publication of the Society for Information Display

INFORMATION DISPLAY

October 1988
Vol. 4, No. 10

Display to print and back
Continuous-tone color printing
Image scanning

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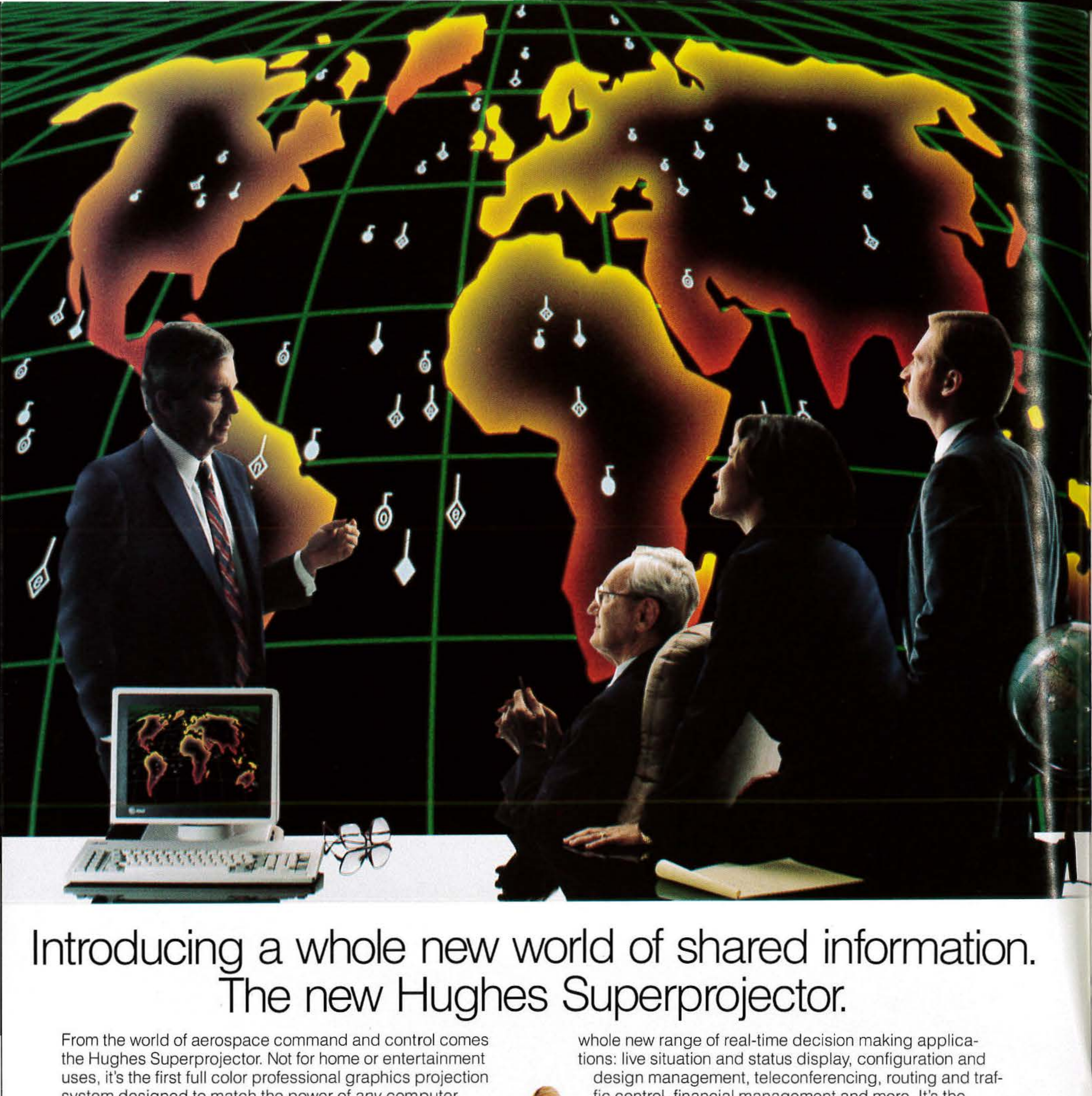

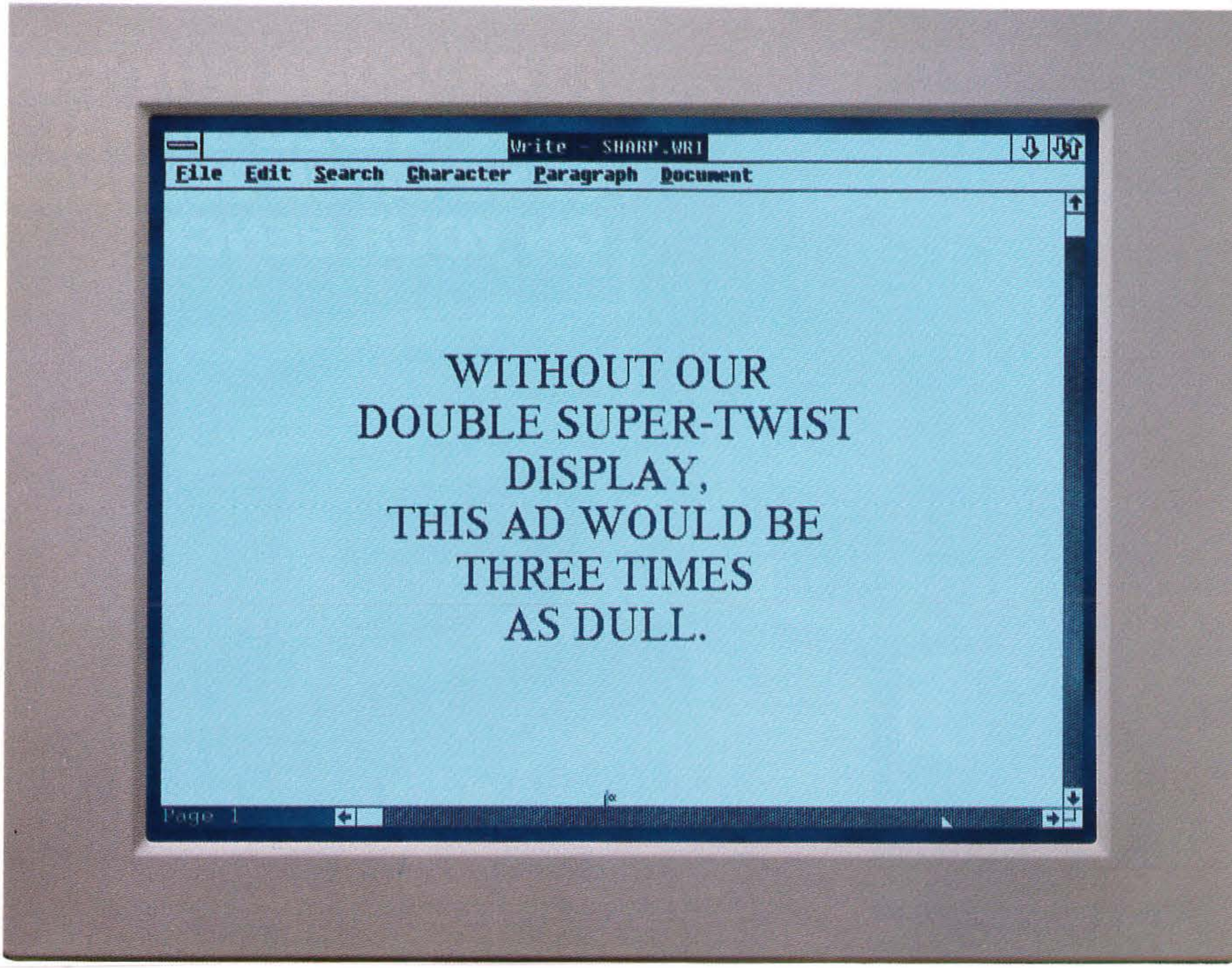

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LM64048Z	640x480	310x240x25	237x180	0.33x0.33
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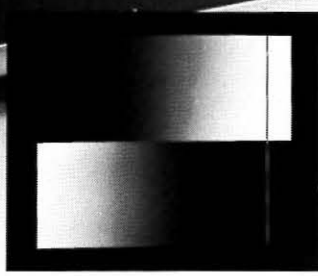

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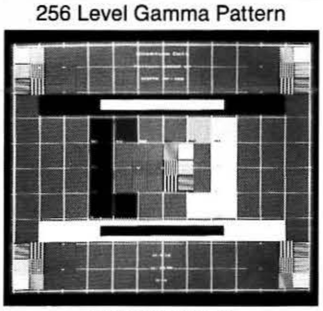

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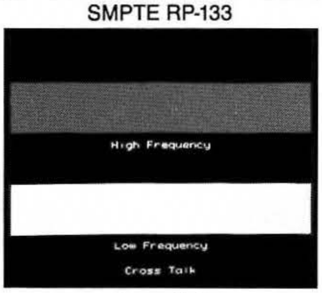
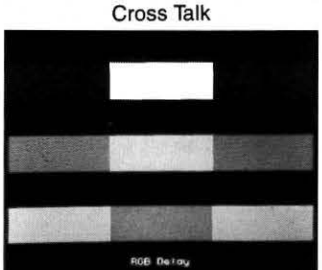


Cross Talk



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Official Monthly Publication of the Society for Information Display

INFORMATION DISPLAY

OCTOBER 1988
VOL. 4, NO. 10

Cover: Roger Penske smiles as Rick Mears qualifies the Penske PC-17 he drove to victory in this year's Indianapolis 500. Artist Joni Carter, who originated the idea of creating computer art of sporting events "on the air," produced this "painting" with TrueVision computer graphics tools. In addition to limited-edition fine art, Joni produces hard copies like this one on Kodak's SV-6500 Color Video Printer, a continuous-tone sublimable dye-diffusion printer. (page 14)

Joni Carter

Next Month in Information Display

Engineering Workstation Issue

- Workstations—new market, new technology
- Displays for engineering workstations
- Graphics workstation standards

Official Monthly Publication of the Society for Information Display
INFORMATION DISPLAY

INFORMATION DISPLAY (ISSN 0362-0972) is published monthly for the Society for Information Display by Palisades Institute for Research Services, Inc., 201 Varick Street, New York, NY 10014; David Slater, Chief Executive Officer; Leonard H. Klein, President; Harold R. Summer, Vice President; Hildegarde Hammond, Secretary; Laura Mangone, Treasurer.

EDITORIAL AND BUSINESS OFFICES: Palisades Institute for Research Services, Inc., 201 Varick Street, New York, NY 10014; telephone 212/620-3371. Send manuscripts to the attention of the Editor, ID.

DISTRICT SALES OFFICES: WEST—Ted Lucas, P.O. Box 852, Cedar Glen, CA 92321; telephone 714/337-6627. MIDWEST—Tom Barron, Pattis/3M, 4761 West Touhy Avenue, Lincolnwood, IL 60646; telephone 312/679-1100. EAST—Becky Akers, Pattis/3M, 310 Madison Avenue, Suite 1804, New York, NY 10017; telephone 212/953-2121.

SID HEADQUARTERS, for correspondence on subscriptions and membership: Society for Information Display, 8055 West Manchester Avenue, Suite 615, Playa del Rey, CA 90293; telephone 213/305-1502.

SUBSCRIPTIONS: Information Display is distributed without charge to those qualified and to SID members as a benefit of membership (annual dues $35.00 U.S. & Canada; $50 elsewhere). Subscriptions to others: U.S. & Canada: $36.00 one year, $64.00 two years, $90.00 three years, $3.00 single copy; elsewhere: $72.00 one year, $128.00 two years, $180.00 three years, $6.00 single copy.

PRINTED by Sheridan Printing Company, 1425 Third Avenue, Alpha, NJ 08865. Third-class postage paid at Alpha, NJ.

POSTMASTER: Send address changes to Society for Information Display, 8055 West Manchester Avenue, Suite 615, Playa del Rey, CA 90293.

editorial

Making paper part of the system

Personal computers and engineering workstations were, according to some visionaries, destined to make paper obsolete. Of course, that didn't happen, and the main problem facing most paper manufacturers at the moment is an inability to supply all of their customers.

But that paperless mindset haunts us to this day—printers are still called "peripherals" even though monochrome text printers using a variety of technologies are ubiquitous. We are, in fact, very far from having a seamless system in which alphanumeric and color graphic information—stored electronically, photographically, or on paper—can be accurately, quickly, and cheaply converted from one form to another at the system operator's convenience.

A particularly difficult part of the problem is color fidelity when making, for instance, a color hard copy of the image on a color display. In our lead article, Warren Rhodes lays out the surprising complexity of the problem and suggests an approach to its solution.

Despite the difficulties, the technology of color graphic printers for business, engineering, and small design studio environments is rapidly improving. The latest approach is continuous-tone printing, in which different shades of colors are printed directly without resorting to dot patterns. Denise Seldon surveys the four leading continuous-tone technologies. On August 30, just as the final copy for this issue was being sent to the printer, Honeywell and 3M jointly introduced to the press and financial analysts their new dry-silver color process, which Denise (one of the press conference's organizers) certainly mentions in her article. At 300 dpi, the resolution is far superior to current sublimable dye-transfer units, while the color gamut is not as good. The process produces very impressive images. Video graphics printers for engineering applications should be available during the first quarter of 1989 for about $10,000.

Photo: NHK Science and Technical Research Laboratories

Printing, however, is not enough. If paper (and photographic film) is to be a natural part of the system, we must be able to do hard copy in reverse—electronic imaging. In fact, imaging can be done to much higher quality than either color printing or color image display on a CRT. But, says Bob DeSantis in our third article, there are many system issues to consider.

continued on next page

editorial

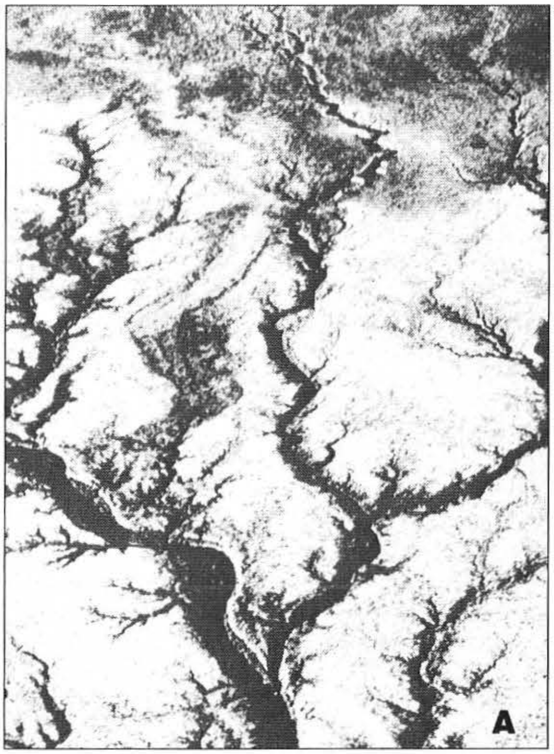
continued from previous page

Also in this issue, Carlo Infante reviews the book *Input Devices*, edited by Sol Sherr.

In the article "Plasma Displays" that appeared in our July-August issue, Fig. 4 (see above) was incorrectly credited. The photograph was actually supplied by NHK, who also produced the 20-in.-diagonal color dc plasma display pictured in the photo. This display, which is typical of NHK's current laboratory units, has a 0.65-mm discharge pitch and good color purity and uniformity.

Making this correction gives me a chance to note that in charting the direction of Japan's broadcasting technology, NHK has established a goal for the size of high-definition TV displays: over 50 in. on the diagonal! NHK's selected technology for future flat-panel large-screen displays is color plasma, in which NHK has had a significant developmental role for the last 15 years.

—Kenneth I. Werner



Delta or Aorta? Which is Which?

No problem here because both of these images were processed on Raytheon's new TDU-850 Thermal Display Unit.

The TDU-850 is the only thermal recorder to display true grey levels (not mere halftone representations) at such high speeds and resolutions. Utilizing 203 dots per inch, the unit offers 64 grey levels and can provide 256 grey levels through the use of super pixels. The TDU-850 is your assurance of high quality images. Standard units about $5,000. (Slightly higher overseas). RS-170 video and IEEE-488 computer interfaces are available.

When you must know what you're looking at, look for equipment that knows what to look for. For details call or write **Marketing Manager, Recorder Products, Raytheon Company, Submarine Signal Division, 1847 West Main Road, Portsmouth, RI 02871-1087. Phone: (401) 847-8000.**

Raytheon

A. Satellite view of river delta. **B.** Arterial angiogram.

Note: These began as continuous tone images which were processed in black and grey by a TDU-850. The TDU-850 images, however, had to be converted to conventional halftones in order to be shown in this magazine. Thus the high quality of the original TDU-850 images have been obscured. For true results ask to see a demonstration.

Circle no. 6

Citations and references misplaced

My article "Plasma Displays," which appeared in the July-August issue of *Information Display*, had an incorrectly credited photograph, as well as omitted references and citations.

Figure 1 of the article, showing the structure of a dc plasma display, should have been referenced to Nakagawa, et al., *National Technical Report*, Vol. 33, No. 1 (1987), p. 109.

Figure 4, which shows a 20-in.-diagonal and a 0.65-mm average discharge cell pitch plasma TV, and its related data were provided by NHK Science and Technical Research Laboratories. (See H. Murakami, et al., Society for Information Display *Digest of Technical Papers*, Vol. 19 [1988], pp. 142–145.)

Five-line/mm data displays were developed by Sony Corp. and later by Photonics Technology. Luminances for dc memory panels of 900-1300 fL were reported by Ferranti Ltd. and by Mullard Research Laboratories, and 16-gray-scale expression by, for example, Dixy Corp. and Oki Electric Industry Co., Ltd.

Siemens AG fabricated 12-in. color CRT dc plasma hybrid displays. Using a similar technique, Lucitron, Inc., also made the 35-in. monochrome and 8.5-in. color displays mentioned in the article.

It should be mentioned that Hitachi is also working towards gas-discharge TV. Our approach is to produce short (~ 0.2 μsec) Xe discharge pulses in a long (~ 2 mm) discharge cell for VUV emission, which results in high-luminance (200 fL) and high-efficiency (1.6 lm/W) displays, with somewhat complicated panel structure.

—*Shigeo Mikoshiba*
Central Research Laboratory
Hitachi, Ltd.
Tokyo, Japan

Address correction

MRS Technology, Inc., was mentioned in Mr. Corless' article "Large Masks for Flat Panels" (*Information Display*, July-August 1988). As Mr. Corless wrote, MRS is the manufacturer of the largest area precision optical stepping tool available today. Unfortunately, our address was listed incorrectly. MRS Technology, Inc., can be found at 10 Elizabeth Drive, Chelmsford, MA 01824; telephone 508/250-0450

—*James D. McKibben*
MRS Technology, Inc.
Chelmsford, Massachusetts

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president's message

Raising standards

Should SID be writing standards? Your first reaction might be, Why of course. Doesn't every professional society? In fact, several engineering societies do not. In its entire 26-year history, SID never has, though we have always had a definitions and standards committee.

Though there were several unfulfilled attempts to write standards, doing so was not that critical in SID's early years. The primary display was the CRT, and older societies, such as IEEE (IRE and AIEE) and EIA, had covered the CRT before SID was born. But times have changed. The flat-panel industry has come of age and new standards are desperately needed. Flat-panel addressing, for instance, is quite different from the situation in a CRT, and is one area requiring standards activity.

SID has become such a dominant society in the display area that there is no longer much technical display activity in other engineering societies—except in the standards arena. By not stepping in to write standards for displays, SID indirectly created a void that is now being filled by SAE, EIA, HF, and other societies.

These societies have their own reasons for writing standards. The issue is not whether these societies are encroaching on SID's territory, but what responsibility SID has as the premier society for information displays.

Some people have said we shouldn't write standards because the civil liability is too great and insurance is too expensive. But wait a minute! Other societies do it, and life must go on in spite of lawyers and civil suits. Our attorney advises us that legal liability from this activity is minimal. Some other people say standards aren't necessary. But those folks probably do not have a recent involvement with product design, manufacturing, procurement, quality control, or inspection.

I have asked Pete Keller, a renowned authority on displays and chairman of SID's definitions and standards committee, to help answer the question, What should SID be doing? He and his committee have been studying the standards question in depth, starting with a Disneyland Hotel meeting in May and continuing with the Hyatt Islandia Hotel meeting in October. We have asked representatives from ANSI, ASTM, EIA, and other organizations to speak at the October meeting. On the basis of these meetings and other inputs, Pete will present a recommendation to the SID board of directors at our May 1989 meeting.

I would sincerely like to know what you think. Please circle no. 99 on the reader response card in this issue if you think SID should be writing standards, or no. 100 if you think we should not. I would also welcome any written comments you would like to put on the card.

—Larry E. Tannas, Jr.

Display to print and back—can you get there from here?

BY WARREN L. RHODES

ANYONE WHO HAS created a color visual on a graphics display, produced a color hard copy, and compared the often very different results, knows that our industry has a serious problem. The problem involves far more than technical fine tuning. The technological issues of color measurement and file standards need to be dealt with, but more important are fundamental issues of color science and perceptual psychology.

With the current proliferation of color display, image processing, and graphics systems and the growing use of color hard-copy output and scanned hard-copy input, the problem of producing monitor and hard-copy images that bear a satisfactory relationship to each other has become urgent. A related issue is simply reproducing an image on different displays from the same RGB file—a file which controls the red, green, and blue phosphor emission intensities—with confidence that its colors are the same on all of the displays.

"Color," what one sees, is a complicated neuropsychological response, and its correlation to the stimulus that produces it—chromaticity—is neither single valued nor simple. Chromaticity is relatively easy to measure. When unambiguous communication is needed, it is chromaticity—not color—that is normally measured and reported using one of the several standard color systems in current use [Table 1]. The situation is further complicated by the use of RGB, which is not related in a simple way to chromaticity and is still further removed from color appearance.

Warren L. Rhodes is a color reproduction consultant based in Altadena, California. In a distinguished career, he headed the Graphics Arts Research Department at the Rochester Institute of Technology for ten years, and was subsequently a principal scientist with Xerox Corp. specializing in color reproduction.

Since computer graphics users interested in color reproduction use RGB, a natural first approach to obtaining a hard copy of a screen display is to convert the display data to printer data by using simple transforms of RGB (such as subtracting the numbers representing their magnitudes from some fixed value). The results using this simple transform have generally been disappointing. These transforms from RGB to CMY—cyan, magenta, and yellow, which are the pigment colors used in reflective image technologies such as printing and photography—almost always produce a disappointing print. Hues in the print are not the same as those on the display, images are usually dull, and the contrast is not pleasing.

More sophisticated approaches have been tried, including some utilizing chromaticity—for example, tristimulus values. The concept of tristimulus values is based on the results of experiments carried on by psychophysiologists of perception over the last century, which have demonstrated that the stimulus that produces color perception in humans can be reduced to three variables, one in each of three different frequency bands. When these tristimulus values are the same, and certain very restrictive conditions apply, the same color should be perceived.

Unfortunately, recent experiments utilizing tristimulus values for display-to-printer transforms are based on the incorrect assumption that if the tristimulus values of the image on the display are matched to the tristimulus values of the print image, the two will look alike. This is not true. These experiments attempted to calculate the tristimulus values of each pixel on the display and to transform them, pixel by pixel, to the amounts of cyan, magenta, and yellow printer colors that would reproduce those same tristimulus values on the hard copy. This approach is doomed to failure partly because color printers based on existing technologies can not produce the tristimulus values of the attractive light-saturated colors so commonly used on displays. (The capabilities of these printers are not likely to change much within our lifetimes.) But a more fundamental problem is that, except in some very limited circumstances, the monitor and print images would not look alike even if their tristimulus values could be matched.

Making displays more like printers

Some computer graphics artists, a group of people who are especially concerned with the color fidelity of prints to their electronic originals, tried to solve this problem by limiting the gamut or range of tristimulus values produced on the display to that available on the printer. Unfortunately, this approach has not achieved the desired result. When it was attempted, the display image was dull and of low contrast, and the print had more contrast than the display.

A less limiting approach is to produce what you like on the display, but to reproduce accurately only those chromatici-

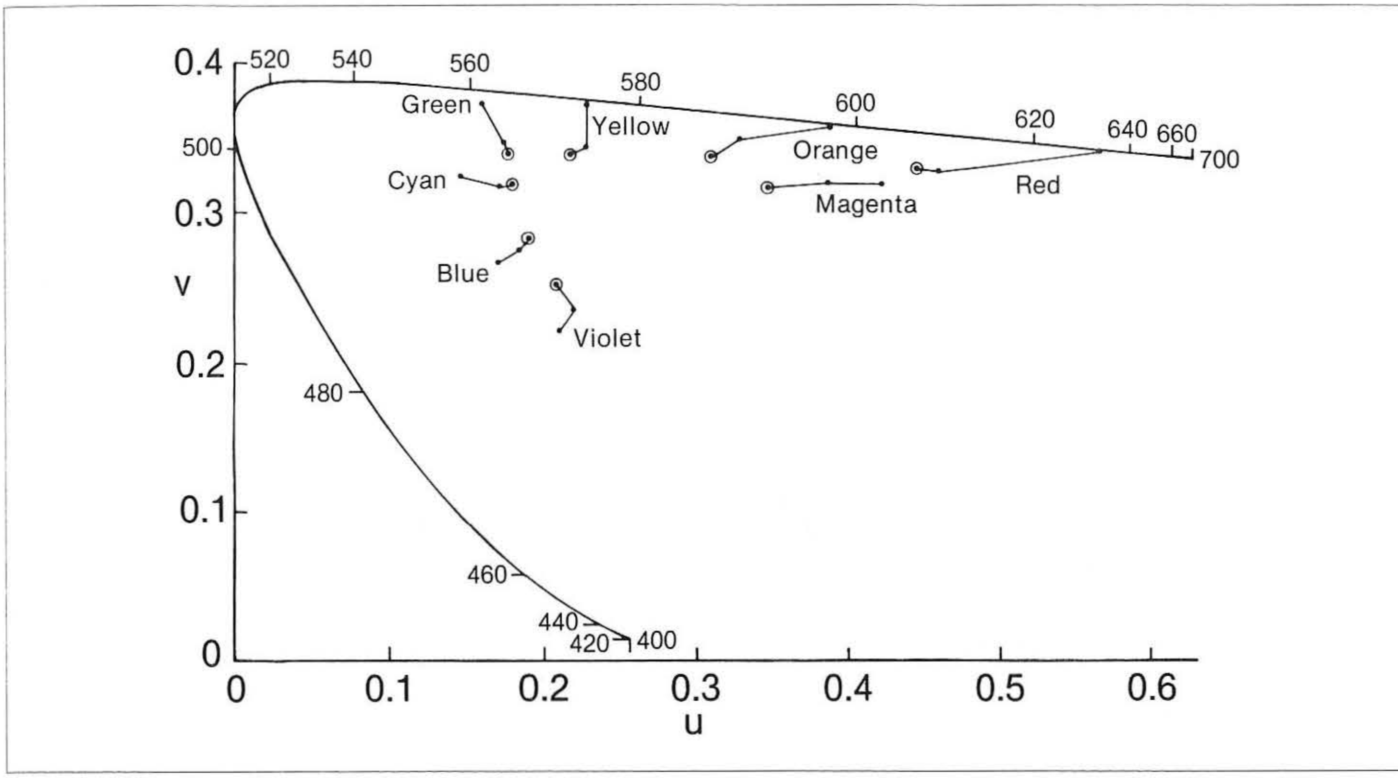

Fig. 1: Trichromatic coordinates in u,v space of a set of reference colors. The luminance level, which controls visual adaptation, is 310 fL, typical of cloudy daylight. The other two points corresponding to each color represent the change in trichromatic coordinates required to produce the same color appearance at lower adapting luminance levels. The outermost points are those required when the adapting luminance is decreased to 2.25 fL, typical of office illumination where displays are used.

ties within the range of the printer. All display pixels with chromaticities outside the printer gamut are reproduced at the boundary of the printer gamut. This approach causes some colors that are different on the display to reproduce as the same color on the print. For many images this loss of color differentiation is unacceptable.

Maureen Stone and her co-workers at Xerox tried proportional compression of display tristimulus values to make them fall within the range of printer tristimulus values. Since this approach produced unacceptable desaturation of some colors, a modification of the approach was used to produce the color illustrations in a supplementary issue of *Color Research and Application.*[1]

Various authors have tried a variety of scalings in different color spaces for transforming the data that drives the display into data that drives the printer. The results in all cases have been less than satisfactory.

Table 1: Chromaticities–Color Stimuli Specification

R G B	Primary stimuli for color matching. They may correspond with CRT phosphor chromaticities.
X Y Z	International Standard Tristimulus values (CIE). Y = Luminance
Y I Q	Linear transform of X Y Z. Used in television for black-and-white compatibility and to reduce transmission bandwidth requirements.
x y Y	Linear transform of X Y Z. Values usually plotted on CIE diagram.
L* u* v*	Linear transform of X Y Z. Values are relative to a reference white. Correlates better with small color difference data.
L* a* b*	Cube root transform of X Y Z. Values are relative to a reference white. Correlates better than L* u* v* with small color difference data.

The confounding perception of color

There are several possible reasons why this approach doesn't work. One is that color is appearance—the mental image evoked by a stimulus. Chromaticity certainly defines a stimulus, but it turns out to be just one of several interrelated variables that influence the perception of color.

Only one precise statement can be made about chromaticity: two colors of the kind called "nonmetameric" will look the same if their tristimulus values are identical and if their areas are the same size and shape, are surrounded by the same color, and are illuminated identically. The kind of colors called "metameric," on the other hand, can look alike in one light source and different in another. This is because metameric colors have different spectral response curves that happen to produce the same tristimulus values when illuminated by a certain light source, though not by others.

Color = physics + psychology

Solving the essentially physical problems of color matching is crucial to obtaining a good relationship between printed images and display images. But while the variables of color matching are important, psychological factors must also be taken into account when correlating colorimetric measurements and color appearance.

Induction is one of these factors. When the sizes of dissimilar color areas are relatively large, each color induces its complement into the adjacent colors. An area surrounded by yellow, for instance, will appear more blue than the same area surrounded by gray. A color surrounded by black will appear lighter than the same color surrounded by white.

The adapting luminance—the average level of luminance to which the eye has adapted while viewing an image—is another important variable in relating chromaticity to appearance, and is significant when comparing images. Colors that look bright and colorful when seen under bright light will not look as colorful when seen in a dimmer light.[2] [See Fig. 1.]

Edge effects also play an important role. Images with sharply defined edges appear more saturated and more contrasty than images with soft edges. Induction, adapting luminance level, and edge effects are some of the factors that are important when comparing two images with different magnifications or sharpnesses. They are even more important when comparing images if the illuminance levels and correlated color temperatures of the illuminants are different: for instance, when comparing a print in a normally lighted room with an image on a display where the luminance is significantly lower. It should be noted that the correlated color temperature of most CRTs used for computer graphics is between 6500 and 9000 degrees Kelvin. The correlated color temperature for the viewing conditions that have been standardized in the graphic arts is 5000 degrees Kelvin.

The color match between a display and a print is always metameric. That means that a match made when the print is seen under one light source will not be a match when the print is seen under a different light source. Of particular importance when comparing an image on a display with one on a print is the "dim surround" effect. Displays look best and are commonly viewed in rooms with relatively low illuminance and where the display is significantly lighter than other objects in the field of view. Under these conditions, viewers feel the display matches a print viewed under normal room illumination when the display's log luminance contrast and purity are actually much greater than they are on the print.[3] This means that computer graphics displays, when viewed under customary dim lighting conditions, show less visual contrast and colorfulness than prints seen in normal room illumination. This is the most important unsolved problem when correlating a display with a print. No general model has been found to predict the necessary transform.

Getting there from here

The search for a suitable transform to convert the data to drive a display into the data to drive a printer is extremely difficult because the relationship between chromaticity and color is very complex and because the two images cannot be directly compared. Despite these difficulties, CRTs are already used extensively as an intermediary even in the demanding application of preparing images for commercial printing—part of the growing trend toward "electronic pre-press." One should not conclude from this either that matching chromaticities is a desirable goal or that display images will look the same as the prints made from them. WYSIWYG—what you see is what you get—is an attractive concept, but it is very far from being a reality in the world of color hard copy.

In some regions of color space, the gamut of most cathode-ray tubes exceeds the gamut of most printers, so it is possible to produce colors on displays that cannot be produced on printers. Unfortunately, these are among the colors users favor when they produce graphic images. The optimum print, then, cannot be a faithful reproduction of the display image—it must be a compromise. The best compromise depends on the originator's preferences, on the colors in the display image, and on the colors available on the printer. Consequently, there isn't any single transform that is optimal for all images. Photographers and printers have learned to make these compromises because colors in scenes cannot be produced on prints, and reproductions made from color transparencies cannot match the transparencies. Proposals have been made for finding a transform that incorporates these compromises and is acceptable for most images.[4]

One approach to these complications is a viewing arrangement that makes the display appear to be a print, and limits the chromaticity gamut of the data in the image file to the gamut of the printing process. This allows the user to modify the color in an image and see the result as it will appear in the print without having to make a print. One limitation of this approach is that reducing the chromaticity of the display white point to 5000 degrees Kelvin makes the display brightness quite low.

Photography points the way

Professionals have learned to use photography with all of its limitations and have produced many beautiful photographic prints and printed reproductions. They manipulate the lighting, add or subtract exposure during printing, and adjust the photographic process to produce prints that satisfy them. They learn by trial, error, and practice what is required to produce the result they want. Printers, too, learn what to expect on a print from an image they see on the display, even though the two do not look alike.

A few objective rules of thumb have been applied, such as adjusting the process so that gray in the original is gray in the reproduction. And tone-reproduction curve shapes have been widely accepted for photography and for reproductions of photographic transparencies.

While these rules of thumb are helpful, they are only part of the process leading to successful color reproduction because color image quality is subjective and not well understood. Arriving at a successful color reproduction method resembles the approach of an artist painting a scene. He looks at the scene and selects from his palette the paint which best represents what he wants to portray. He applies the paint and looks at the result. He repeats the process until he is satisfied. He learns through experience what works and what does not—that is, he finds a transform that suits him. Given the tools to manipulate color, practitioners of computer graphics will also learn what gets results and what does not. From this experience, which has yet to be acquired, it will be possible to derive a transform which does the right thing on the average. Individual images may require a modification of the standard transform to produce a satisfying print.

In the end, standards

When an acceptable transform has been found, it will probably be suitable for only one display and printer pair. The RGB pixel values in the image file used to drive the display will have a fixed relationship to the tristimulus values of the pixels on the display, within an acceptable tolerance. If a user wants to see an image created by someone else, his display must have the same relationship between RGB and tristimulus values as the originator's display, and the ambient illuminance color and level must be the same as the originator's.

All monitors are not likely to have the same characteristics even if they are the same model, and the performance of any individual monitor is variable. A reliable colorimeter is required to calibrate the monitor and to keep the performance constant.

The goal is to make it possible for users to exchange files, and for every user to be able to see the image that its author created. An image should look the same on any display. This requires chromaticity standards for image file data, for display calibration, and for room ambient lighting.

If the originator intended the file to be printed, then the tristimulus values in the file should be the tristimulus values of the print the originator produced. For the user to see what the originator intended, his printer must have a capability equal to the originator's. He must know the relationship between cyan, magenta, yellow, and black, and the corresponding tristimulus values, and he must view the print in the same illuminant color and intensity as the originator. To accomplish this, the user's and originator's printers must be calibrated, and the viewing arrangement for the print must be defined.

If the user wishes to print an image created for a display, he may make trial prints and modify the data in the file until he gets the desired result, or he may make use of a "standard" transform. A "standard" transform necessarily assumes a "standard" display and a "standard" printer, each with a "standard" viewing arrangement. A similar problem confronts the user who wishes to display the image of a file intended for printing. If a transform exists which allows the display and print images to look alike, the inverse transform is simple. If not, an inverse transform will have to be found.

In the traditional graphic arts, learning the techniques for producing handsome images requires skill and extensive training. Practitioners of computer graphics have demonstrated little patience for this approach, but until standards are developed, there will be no alternative for those images for which color fidelity is an important consideration.

Notes

An extended version of this article will appear in the *Proceedings of the SID*, Vol. 30, No. 1, to appear in mid-1989.

[1]M. C. Stone, J. Beatty, and W. M. Cowan, "A Description of the Color Reproduction Methods Used for this Issue of *Color Research and Application*," *Color Res. and Appl.*, Vol. 11, Supplement 1986, pp. S83–S88.

[2]R. W. G. Hunt, *The Reproduction of Colour* (New York: John Wiley and Sons, 1967), pp. 126–128.

[3]C. J. Bartleson's "Color Perception and Color Television" (*Journal of the Society of Motion Picture and Television Engineers*, Vol. 77, No. 1 [1968], pp. 1–12) is an excellent review of the role of the viewer in color television.

[4]M. G. Lamming and W. L. Rhodes, "Towards WYSIWYG Color, A Simplified and Subjective Method for Improving the Printed Appearance of Computer Generated Images," EDL 88-2, Xerox Palo Alto Research Center, 3333 Coyote Hill Road, Palo Alto, California 94304. ■

Continuous-tone color hard copy

BY DENISE SELDON

COLOR SCANNERS capture images at far higher quality levels than today's color hard-copy systems can reproduce. As a result, hard copies do not adequately support high-performance color image processing, and their support of computer graphics and computer-aided design (CAD) systems is limited.

But industry is responding to this challenge with new approaches. Foremost among these is continuous-tone hard copy, in which each pixel can be varied in density and hue. Several continuous-tone hard-copy technologies are available, each offering distinct strengths and weaknesses [Table 1]. It is not yet clear which technology will dominate, but users and system integrators will soon have access to high-performance continuous-tone hard-copy systems.

Dithering with current technology

Most of today's color hard-copy devices can print up to seven colors. To produce shades of those colors or new colors composed of them, these devices use dithering—the establishing of dot patterns to produce a color. Each pixel becomes part of a 2 × 2, 3 × 3, or 4 × 4 matrix called a superpixel. To produce orange, for example, a 3 × 3 superpixel may contain six red pixels and three yellow pixels. A light shade of blue may contain seven blue pixels and two white pixels.

Continuous tone, on the other hand, varies the color of each individual pixel. Lighter shades are produced by decreasing the amount of dye used to color the entire pixel. This is related to the century-old process of "halftoning," which varies the size of the ink dot within each pixel—and therefore the amount of white space surrounding the dots—to produce lighter or darker shades of each color. (All of the photographs in this magazine are reproduced by halftoning.)

Why continuous tone?

The most obvious advantage of continuous tone over dithered color is resolution. A dithered printer converts each pixel on the display's screen to a superpixel matrix on the hard copy. With a 4 × 4 superpixel, the effective resolution of a nominal 300-dpi system is 75 dpi. With continuous-tone printers, the effective and nominal resolutions are equal.

High resolution is an increasingly important feature of graphics, imaging, and CAD systems. Many monitors today display 1280 × 1024 pixels, and even higher resolutions are no longer rare. At 300 dpi, a continuous-tone hard-copy recorder can easily reproduce 2400 × 3000 pixels on an A-size print. With a 4 × 4 superpixel for each screen pixel, however, a 300-dpi dithered recorder fits only 600 × 750 pixels on an A-size print.

So, continuous tone seems preferable to dithered color. However, halftoning can have the same effective resolution as continuous tone. The dot size is varied, but the dots can have a one-to-one correspondence to the displayed image. However, halftoning is more difficult to implement than continuous tone. To avoid the appearance of a moiré pattern in the halftone dots, the print screen must be turned through a predetermined angle when the color separations are made. No halftone computer graphics printer is commercially available at this time.

More significant, both dithered color and halftoned color use white space to achieve different shades. Continuous tone does not, and provides smoother, more uniform images as a result (see cover photograph). Smooth uniform transitions between shades is important in such applications as medical imaging and thermal analysis. Medical imaging uses different colors to show such things as the direction of blood flow within a vessel. Shades of the colors define the speed with which the blood is moving. In thermal analysis, colors and shades of colors represent different temperatures within the object being analyzed. A continuous-tone hard copy can show the changing values of various parameters more precisely than dithered or halftoned images because white space within a shaded area is not required.

There are dissenting views on how many different shades the human eye can differentiate. A medical image or thermal analysis may use up to 16 different shades of a color to represent the range of values for a given parameter, and most people can differentiate 16 shades. With 32 shades (offered by many continuous-tone implementations) the transitions between the various shades become indistinct for many (if not all) people. Dithered systems must use a 4 × 4 superpixel to produce their 16 shades of a color, and effective resolution suffers.

Denise Seldon is business development manager of Honeywell Test Instruments Division's Graphics Business Unit, located in Denver, Colorado.

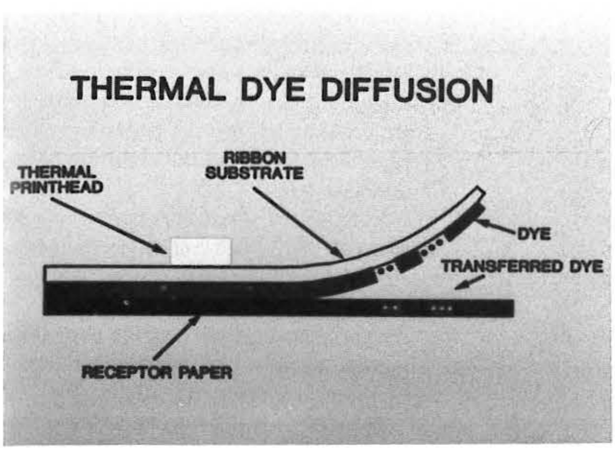

Fig. 1: In sublimable thermal dye diffusion, thermal heads heat dyes on a donor sheet. The heated dyes diffuse into the receptor sheet.

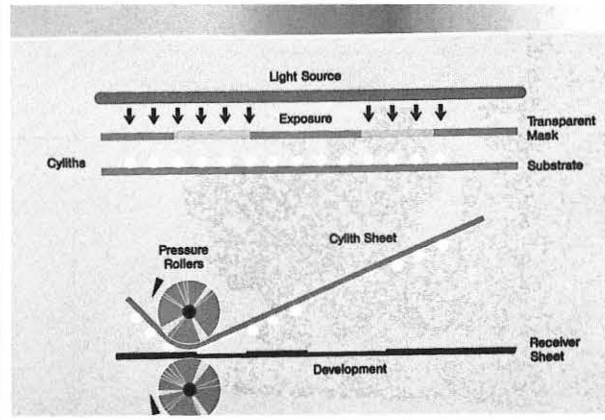

Fig. 2: Microcapsules on a donor sheet are exposed to light, then pressed onto a receiver sheet in the Mead microencapsulated imaging system. Those microcapsules that have been exposed become hard and do not rupture under pressure. Unexposed microcapsules do rupture to form a latent image on the receiver sheet, which is heat developed and fixed.

Any computer imaging application that attempts to duplicate a real object needs both high resolution and smooth uniform shading. Of the three available methodologies, continuous tone comes the closest to duplicating what real objects look like.

A final advantage of continuous tone is the decreased processing required to produce a print. A color does not have to be translated into a superpixel or dot size. The one-to-one correspondence of pixels within the computer image to pixels that appear on the hard-copy output reduces processing time. This can be a significant factor, particularly on smaller host computers.

Significant parameters

Continuous-tone hard-copy products that can produce full (A-size) prints will be available in the near future, and smaller-format printers are available now. When choosing a continuous-tone hard-copy recorder, several factors should be considered.

• *Resolutions* on continuous-tone products are expected to range from 125 to 300 dpi. Some printers will be able to place dots only at fixed locations; others will be able to address nearly any point. High addressability permits changing the printer resolution to match the input resolution.

• *The print speeds* of products currently under development are expected to vary widely. A-size hard copies will probably take from 30 sec to several minutes. Prices are not yet available for all products, but they, too, are expected to be highly variable. Costs per print are expected to range from $0.59 to $5 or more.

• *Strip-chart capability* may be desirable for replacing black-and-white strip-chart recorders in some applications. Whether or not color becomes essential for these applications, the capability is likely to be appreciated if only to permit the purchase of one piece of equipment instead of two.

• *In applications where security* is a factor, printing processes that produce no secondary or residual records may be particularly attractive.

Which continuous-tone technology?

Currently, color hard-copy recorder manufacturers are actively developing four continuous-tone technologies: photographic, sublimable thermal dye diffusion, dry-silver color, and microencapsulated imaging.

Photography, in which photographic paper is exposed to visible light and chemically developed, is certainly the best-known continuous-color imaging process. Of the four technologies, it is also the slowest and most expensive.

Instant photography products that interface with digital displays are manufactured by Polaroid and Matrix. A typical instant photography system takes several minutes to produce a 3¼ × 4¼-in. image. Resolution is 125–300 dpi. The number of producible colors varies by product. Polaroid offers 72 colors, and Matrix offers eight bits per primary (for, theoretically, over 16 million different colors). The cost per print of a 3¼ × 4¼-in. image is about $1. Polaroid 8 × 10-in. color film currently costs $8 per print.

In sublimable thermal dye diffusion, thermal heads heat sublimable ink, which then vaporizes onto the receiving paper [Fig. 1]. This is similar to the process used in conventional wax thermal dye transfer, with the significant difference that the dye diffuses instead of melts. The heat level of the thermal head for each of the three primary colors dictates the density and hue of each pixel. Sublimable dye provides good vibrant colors, but the process takes time because three passes are needed to produce an image. A negative image is left on the dye medium—a possible concern in high-security applications.

Sublimable dye diffusion products are offered by Hitachi, Kodak, and Sony. They produce a 4 × 5-in. print in about 80 sec. Hitachi and Mitsubishi are developing products that will produce A-size prints in 180 sec.

Sublimable dye diffusion products currently produce 32 shades of each primary, resulting in 32,768 different colors. Resolution for the current products is 150 dpi. The cost per 4 × 5 print is approximately $1, and A-size prints are expected to cost $3–5.

Mead Imaging is manufacturing microencapsulated imaging paper [Fig. 2]. The paper is coated with light-sensitive microcapsules of dye. To produce an image, the Mead product requires three steps. First, the donor sheet is exposed to

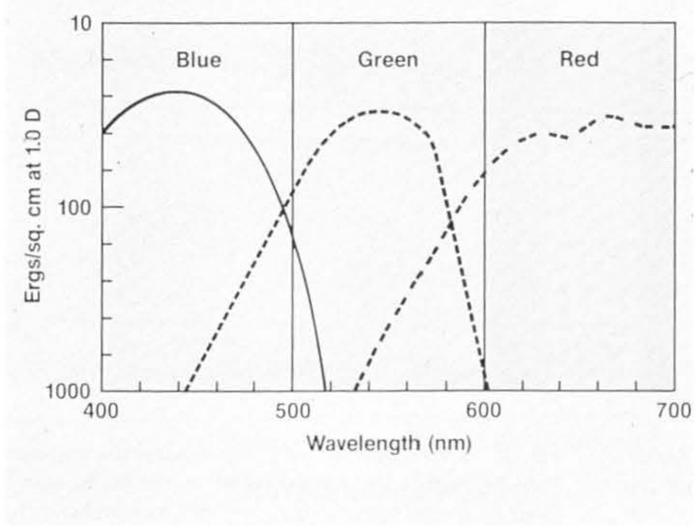

Fig. 3: The three dyes within 3M dry-silver paper are sensitive to a range of light wavelengths. The hardware must supply light sources that match each dye's wavelength sensitivity without overlapping into the next dye's sensitivity range. After exposure, dry-silver paper is heat developed.

light. Exposed microcapsules harden and will not release dye. Next, the donor sheet is rolled against the receiver sheet. Unexposed microcapsules are ruptured and release dye onto the receiver sheet. Finally, the receiver sheet is heat developed.

Mead is manufacturing the media and is working with other companies to develop the hardware. Uniformity of color, especially in medium-to-light shades, has reportedly been difficult to obtain. An additional difficulty is that a large amount of light energy is needed to expose the paper. Current raster exposure methods cannot supply the required light energy in a short amount of time. No computer graphics printer has been announced thus far, but Noritsu is using the Mead product in a 35-mm slide copier. Because the entire paper can be exposed simultaneously in this format, the first print of a slide takes only 35 sec, with subsequent prints requiring only 20 sec. The cost per A-size print on the Noritsu system is $0.59.

3M has developed dry-silver color paper. Like photographic paper, dry-silver color paper is light sensitive. Three different wavelengths of light activate each of the three primary color dyes within the paper. The paper is then heat developed. Dry-silver color paper is simple to use, since no donor medium is required. A single pass can expose the paper for all three primary colors, and the resulting color quality is good.

Each of the three dyes is sensitive to a range of light wavelengths so the hard-copy device must utilize three light sources each of whose wavelengths match the spectral sensitivity of the corresponding dye without overlapping into one of the other dyes [Fig. 3].

Honeywell is developing a dry-silver color hard-copy recorder which will use the 3M paper. A-size prints will be produced in less than 30 sec. Up to 32,768 colors (32 shades per primary) will be available, and the resolution will be 300 dpi. The product will have strip-chart capability. The cost per A-size print is expected to be less than $1.

An optimistic conclusion

The driving force for better color hard copies has been and will continue to be the advances in color CRT technology. It now seems a simple matter of time before hard-copy recorders are able to produce prints that parallel the quality of displayed images. In pursuing this goal, manufacturers have already started moving toward continuous-tone technologies. As industry closes the technological gap between what is seen on the screen and what shows up on paper, we can expect hard copy to become an increasingly important element of imaging, graphics, and display systems. ■

Table 1: Comparison of Continuous-Tone Technologies

	Sublimable Dye Diffusion	Mead Micro-encapsulated Imaging System	Dry-Silver Color	Instant Photography
Speed	80–90 sec for a 4×5-in. print	Potentially fast, if sufficient energy can be delivered for exposure	Less than 30 sec for A-size print	Several minutes
Resolution	150 dpi	Limited by exposure method	300 dpi. Limited by exposure method	125–300 dpi
Cost/A-size print	$3–5	Less than $1	Less than $1	$8
Image quality	Good. Sometimes banding	Good. Uniformity of image is difficult to achieve	Good	Good

Hard copy in reverse

BY ROBERT DESANTIS

JUST AS THERE IS increasing demand for high-quality hard copies of image data files, so is there increasing demand for the conversion of hard-copy image data into electronic form. The process is generally called electronic imaging, and it has found a variety of applications, including graphic arts pre-press systems, photo-retouching systems, remote-sensing systems, and medical diagnosis and storage systems [Fig. 1]. The original hard-copy medium may be a photograph, negative, printed page or, to push the definition of "hard copy," a real-world image. These images can be digitized using a number of different techniques, each having its own advantages and disadvantages. Once an analog image is converted to digital form, it can be manipulated, stored, or transmitted using computers and application-specific electronic systems. The proliferation of low-cost high-performance personal computers and engineering workstations has created a surge in electronic imaging.

Electronic image data

Typical electronic images consist of two-dimensional arrays of picture elements, or pixels. Each pixel may range in depth from 1 to 12 bits per color. In addition, the array may range from 256 × 256 pix-

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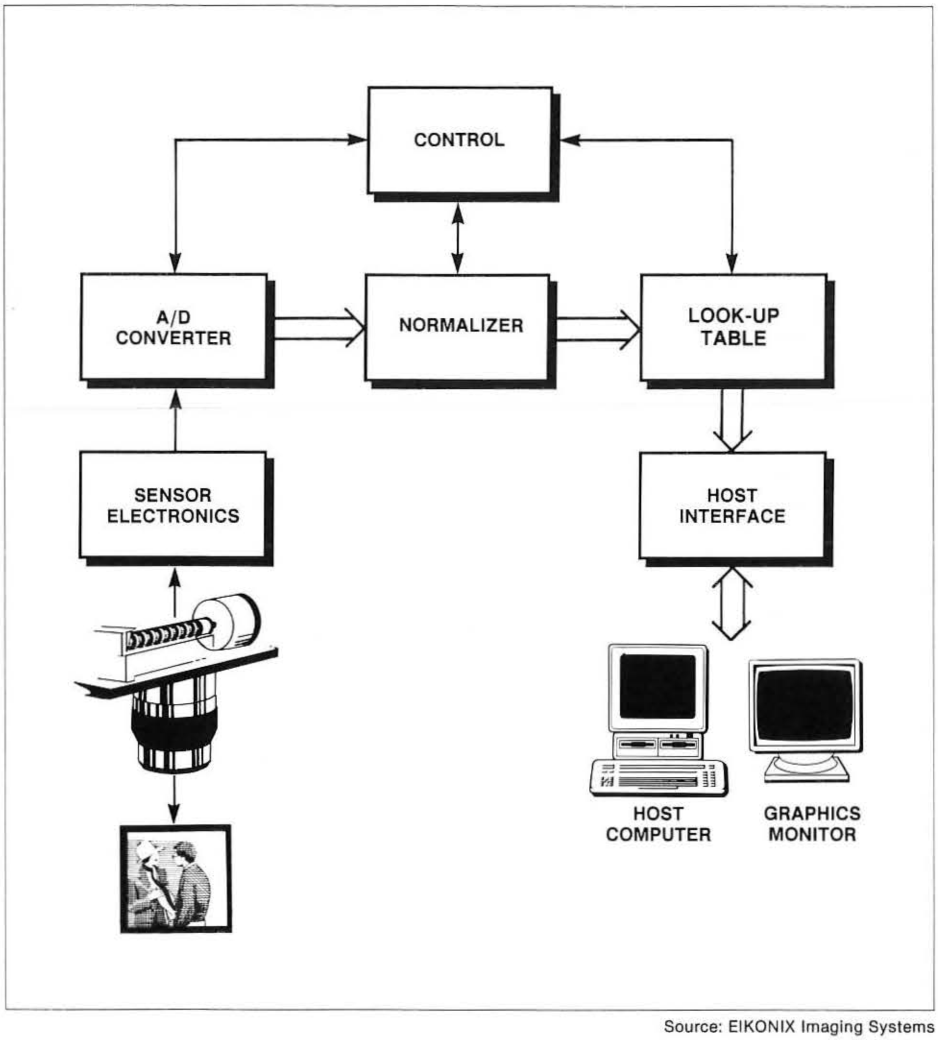

Source: EIKONIX Imaging Systems

Fig. 1: An electronic imaging system begins with the hard copy being imaged through a lens onto an image sensor. Here, the linear CCD array of an overhead scanner and its indexing lead screw are suggested. Sensor electronics and A/D conversion produce a bit-mapped image that is normalized to correct for variations among the sensor elements. Look-up tables provide a convenient way of processing the image, which is finally passed on to the host computer and its graphics monitor.

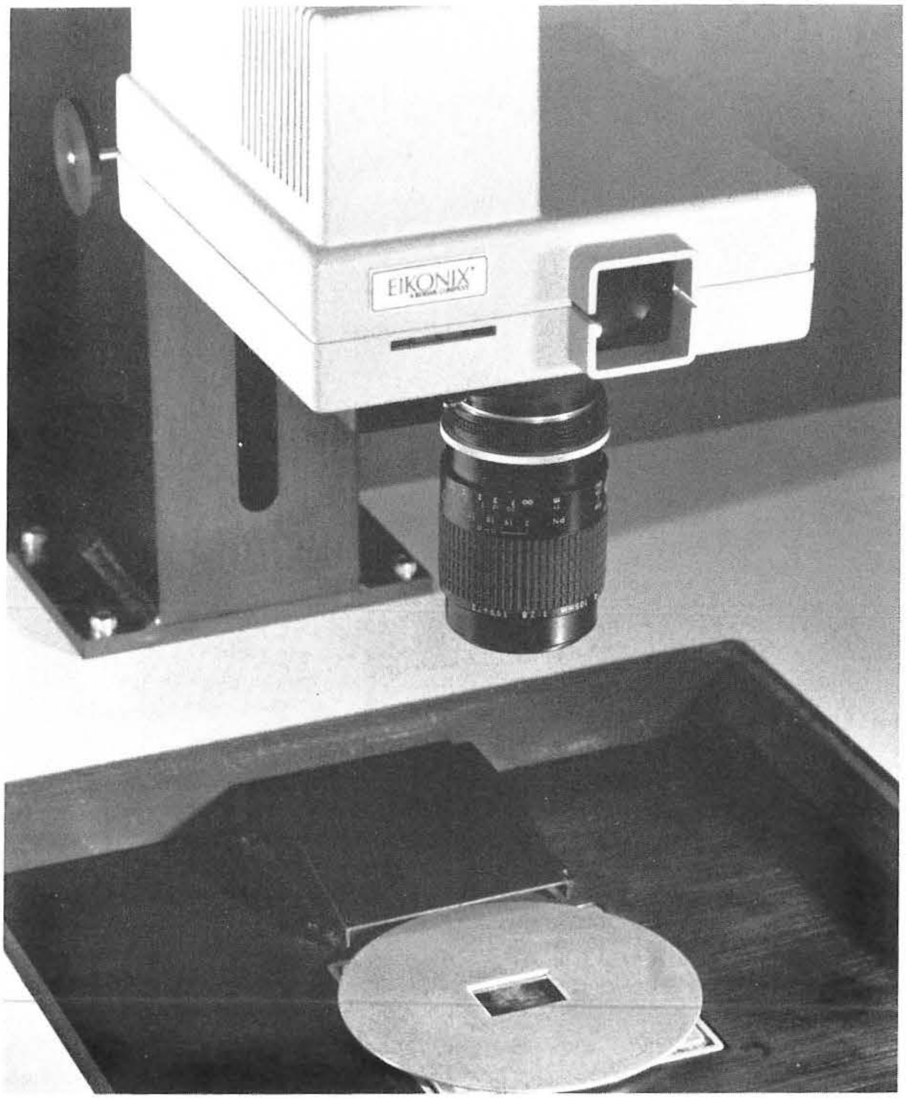

Photo: EIKONIX Imaging Systems

Fig. 2: An overhead image scanner in which a 4096-element linear CCD array (located in the head unit above the lens) is stepped through 4096 positions in the film plane by a lead screw to produce a 4k × 4k-pixel image. Such scanners produce high-quality images from a wide variety of flat and three-dimensional media but require reasonably skilled operators.

els to 4096 × 4096 pixels, or more. Recent developments in high-density memories, high-throughput buses, optical storage devices, and 32-bit microprocessors have made moving, storing, and manipulating large images much more cost effective.

These memory and transmission advances have also improved the quality and resolution of display systems, which has opened new applications. Newspaper photographers can now digitize negatives in remote locations and transmit the information over telephone and satellite links to the home office in time for the morning edition. Advertising agencies can create finished ads on a computer screen, perform changes interactively with the client, electronically generate final proofs, and produce plates for presses. Hospitals can electronically store x-rays and CAT scans in centralized patient databases and distribute them via local area network to offices, examination rooms, and operating suites. This promises to solve the serious problems radiology departments now have in finding adequate storage space for hard-copy x-rays and in retrieving them when they are needed.

How do you digitize an image?

Images can be captured for digitization with a number of technologies, including vidicon tubes, lasers, linear charge-coupled device (CCD) arrays, and area CCD arrays.

Vidicon tubes, which look much like CRTs, are the most common. The end of the tube is sensitive to visible light, and each sensing location on the tube produces a voltage corresponding to the intensity of light striking it. An electron beam scanned across the sensitive area is modulated by the voltages produced by each pixel. Vidicons traditionally have a spectral resolution, or dynamic range, of only 6–7 usable bits per pixel, and their spatial resolution is generally limited to 256 × 256 pixels.[1] There are a number of newer vidicon and vidicon-like sensors, however, that claim to achieve 1024 × 1024 resolution. Vidicon cameras can capture images in "real time," usually 1/30 sec or less. They are relatively inexpensive compared to laser, drum, and CCD scanners, and are quite adequate for applications that demand no more than their limited spatial and spectral resolutions.

A number of high-end scanners have been developed using a laser to scan directly across a reflective or transmissive hard-copy medium. The scan is first across each row and then down, as in a noninterlaced CRT. A sensor element (usually a photodiode) produces a charge proportional to the reflected or transmitted light. This charge is then converted into a voltage which is represented digitally, usually by an 8-bit value ranging from 0 to 255. Because laser scanners use coherent light they can achieve very high spatial resolutions, but because the light is monochromatic these machines can not produce color scans and are generally not used on color originals. The drum scanners traditionally used in the graphic arts industry employ similar technology, but they generally use focused white light instead of a laser, which permits the scanning of color originals, and a photomultiplier tube to count charge. A flexible original photograph or transparency is mounted on a drum, which turns while a scanning head traverses from left to right, thus scanning in a helical pattern. Both laser and drum scanners offer high spatial resolution, but cost much more than other scanners. Drum scanners have the additional drawback of being extremely slow.

CCD scanners come in two flavors. The most common uses a two-dimensional area array of photodiodes, usually 512 × 512, which is masked onto a silicon substrate using traditional semiconductor techniques. Each diode is coupled to a register that stores charge; hence, the name charge-coupled device or CCD. The registers are laid out in rows and columns, and are read out one row at a time. The charge stored in each element is converted to a voltage which is usually digitized to 8 bits. These devices are used in many applications as replacements for vidicon technology. Because of the large number of CCD elements that must be etched—a 512 × 512 array contains 262,144 cells—area arrays have been limited in size. Today the largest area array available commercially has 1320 × 1035 elements—over 1 1/3 million pixels. Arrays of this size have a higher spatial resolution than vidicons and scan in real time, but are difficult to manufacture. Yields are low and costs are high due to the large number of photosites.

Linear CCD arrays offer considerably higher spatial resolution, but at acceptable cost. These devices have a single row of photodiode elements. Sizes range from a few elements up to 4096 photosites, with 8192-element devices in development. These arrays can be precisely scanned across a substantial field of view for high resolution in both dimensions. A 4096 × 4096 scan results in 16.7 million pixels. A high-resolution scan takes time, and the time required is the major drawback of linear array scanners. These scanners are slower than area CCDs or vidicons but considerably faster than drum or laser scanners. Linear CCD scanners also cost much less than drum or laser scanners.

Scanning for color

By scanning the object plane three times, each time with a different color filter, a color representation can be generated. The most common and most economical implementation of this approach uses a filter wheel with a red, green, and blue (RGB) filter. A color image is constructed by combining the corresponding pixels from each scan. If each scan generates an 8-bit gray scale, the resulting color image is said to be a 24-bit image. An alternate approach utilizes three sensors rather than one, each with its own filter. This cuts scan time by two-thirds, but adds to cost and complexity.

The long gray silicon line

Linear CCD scanners provide a cost-effective approach to high-resolution scanning of still objects. Because of the limited number of photosites, the units can be relatively inexpensive compared to area sensors while offering superior resolution. And because data is generated one line at a time, there is no need for the costly frame-store memory required by vidicon and CCD area sensors.

The operation of a linear scanner is straightforward. The sensor is placed behind a lens in what is called the "film plane," in analogy to photographic cameras. The medium being scanned is imaged onto the sensor. Either the sensor is stepped through the film plane, thereby capturing each line of the image, or the medium is moved through the image plane, exposing one line at a time to the fixed sensor.

The first method offers the most flexibility. By placing the moving array in a scanner head, the digitizer can be used much like a 35-mm camera. It can be pointed at transmissive or reflective media, and the spatial resolution can be varied simply by changing the distance from the scanner to the medium. This also permits the medium to be as large or as small as desired. It also allows the scanning of three-dimensional objects [Fig. 2].

Fixed-sensor scanners are found in a range of applications, from page scanners for optical character recognition (OCR) to low-end facsimile machines. This approach works well in those applications where the medium is predictable and not highly variable, which is frequently the case when office documents are scanned.

The edge of night

Because the CCD array is a silicon device, each element has a slightly different response to light. If the entire sensor is put in the dark, a small variation would be found in the "dark current" produced by each photosite. When spectral resolution is important, it is necessary to avoid dark-current variations, which can cause streaking in the dark areas, or "shadows," of the image. There will also be variations in the bright areas of the image, which are called "highlights."

Dark-current error can be corrected by measuring the dark-current value for each element and subtracting it from the signal generated by each photosite during scanning. Multiplying this result by a gain factor corrects for full-scale nonuniformities. These corrections, together called normalization, are crucial to generating good reproductions of a scanned image.

Some scanners, such as the EIKONIX 1412, use low-noise electronics and a 12-bit analog-to-digital (A/D) converter to generate 4096 levels per color for each pixel. Twelve bits per pixel at the front end result in a minimum signal-to-noise ratio for the scanner system of 1000:1. This generates a true 10 bits per pixel after noise and normalization, allowing the scanner to discriminate down to optical

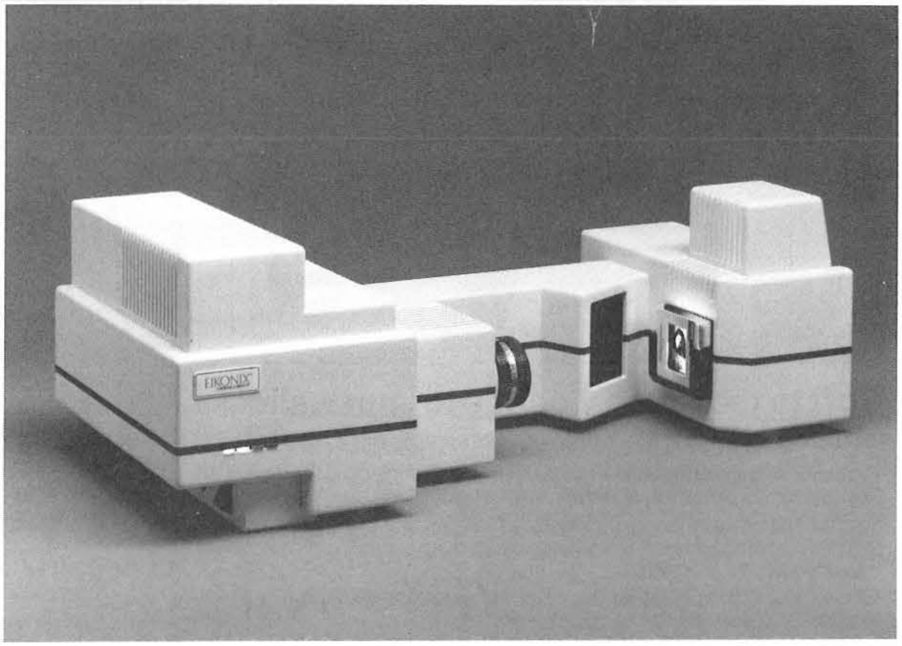

Photo: EIKONIX Imaging Systems

Fig. 3: *An example of the new generation of format-specific image scanners is the EIKONIX 1435 Slide Scanner. It is restricted to the imaging of 35-mm slides and film strips, but offers high throughput, a 12-bit/color dynamic range, and an impressive 2800-dpi resolution—enough to capture all the information on the film.*

densities of 3.0—far into the shadow detail of the original photography. These high spectral resolutions are required for medical imaging of x-rays and commercial printing, among other applications.

Processing the scanned image

Once the scanned data has been digitized and normalized, a look-up table (LUT) can map it into another image space. A LUT can be thought of as a memory device in which the incoming data is treated as a memory address. Stored at each location is a corresponding output value that becomes the new data value. LUTs can be used for a variety of purposes. By setting a threshold, gray-scale data can be binarized. Entering an inverse ramp turns a positive into a negative, or vice versa. A square-root curve boosts the data in the shadows at the expense of the highlights. LUTs are an important part of scanning and can be implemented in either hardware or software. Hardware LUTs greatly decrease scan time, but can add to system cost.

Taking the bus

Most scanners act as peripheral devices to a host computer, and data are passed between them over one of the many standard or proprietary buses. Because images generate large amounts of data, parallel buses are the only ones that make sense. Most scanners available today use the IEEE-488 bus (GPIB), but this bus causes transmission bottlenecks, particularly for area array scanners. So, scanner manufacturers are now looking at the small computer system interface (SCSI) bus. The latest revision of the ANSI SCSI (often pronounced "scuzzy") specification includes a protocol specifically for scanners.

The size of the data file generated at the host computer and the required data transfer rate are important aspects of digital scanning for system integrators and end users. A 1024 × 1024 area array generates 3 Mbytes for a 24-bit color scan. File sizes for scans done with a 4096-elelent linear array increase to 16 Mbytes for an 8-bit scan and to 48 Mbytes for a 24-bit color scan.

The scan time for a linear CCD scanner depends on a number of factors, including the amount of time that each line must be exposed to light—called the integration time. This ranges from 4 to 30 msec, depending on the object being scanned, the light available, and the distance to the object. The array must step 4096 times for a 4k × 4k scan, and three times that for a color scan. The minimum scan time can be calculated by multiplying the number of lines by the integration time per line. Color scans may require a different integration time for each color to balance the scanner. The blue scan is usually the longest, since blue filters have lower transmittance and photosites are less sensitive to blue wavelengths. (See accompanying article, "Calculating Scan Time.")

For area sensors, the scan time becomes the integration time, since all of the elements are exposed at the same time. This allows real-time scanning with area CCD sensors. Real time is traditionally defined as 30 frames/sec, which requires integration times of 33 msec or less. This would require 11 msec for a color scan using a rapidly spinning filter wheel. Most home video cameras use a low-resolution area array with a spinning filter wheel or use three arrays, each with its own filter. But a three-array approach requires much more precise optical and mechanical alignment.

Format-specific scanners

Since the advent of the microprocessor in the early 1970s, scanner technology has advanced rapidly, and the prevailing philosophy has changed. Twenty years ago, digital scanners were built on a contract basis for government and military research. The descendents of these devices were packaged for commercial use during the late 1970s. The EIKONIX 78/99, a typical overhead scanner of this era, was designed for laboratory use and intended for interfacing to a PDP-11 or similar minicomputer. The machine included a rack of electronics and a scanning head that housed the linear CCD sensor and the A/D converter. Such machines were expensive and difficult to use, but were used to digitize everything from a DNA double helix to the Shroud of Turin.

With the microcomputer revolution, low-end gray-scale page scanners became available. These devices were typically designed to scan only 8½ × 11-in. paper. They were low-resolution devices that could not scan color originals, but these single-format scanners were successful as input devices for OCR and early desktop

Calculating scan time

The minimum scan time for a 4096-element linear array performing a 4096-line color scan depends on the different integration times for the different colors:

4096 lines of red times 6 msec/line
= 24.576 sec for RED scan
4096 lines of green times 4 msec/line
= 16.384 sec for GREEN scan
4096 lines of blue times 8 msec/line
= 32.768 sec for BLUE scan

The minimum scan time is 73.728 sec for a three-color scan. To this must be added the time to return the stage to home between successive color scans and the time to change the filter. This is on the order of 15 sec. The result is a *total scan time* of about 90 sec for this example. Note that if three sensors were used in parallel, each with its own filter, the scan time would drop to the longest scan time for an individual color—33 sec in this example.

publishing. Flexibility was traded for economy, throughput, and ease of use.

Variable-format scanners still exist. EIKONIX's modern successor to the 78/99 is the 1412 scanner. This 4k × 4k, 12-bit device is also an overhead scanner, but the extensive support electronics have been miniaturized and placed inside the scanner head. This makes overhead scanning less expensive and far easier to do.

Two new kinds of format-specific scanner constitute the latest stage in digital scanning's development. Color page scanners are capable of scanning up to 11 × 17-in. reflective or transmissive copy, though the fixed linear CCD array they typically use limits them to scanning at a single spatial resolution—usually 300 pixels/in. These machines have seen widespread use in applications that do not require the versatility and high spatial and spectral resolution of overhead scanners.

The second type of format-specific scanner is the color slide scanner [Fig. 3]. One of the first of these to become available is the EIKONIX 1435 Slide Scanner, which easily captures color or monochrome 35-mm slides for use in a host computer. The 1435 digitizes at 12 bits/pixel per color and has a fixed spatial resolution of 2800 pixels/in., which is enough to resolve all of the useful data stored on the original film. Therefore, a slide or section of a slide can be scanned and then enlarged digitally rather than optically. Changes and corrections can be made interactively on a host computer, and visual and electronic output can be generated. This device opens the possibility of a revolution in the traditional photography industry. Since color negatives can be scanned and converted to positives using on-board LUTs, slide scanners of this quality could make the photographic enlarger a thing of the past.

With the move to user-friendly fixed-format scanners, electronic imaging is likely to continue its penetration of the office and industrial environments. As high-resolution color displays, color output devices, and color copiers proliferate, and as color images become an increasingly necessary part of business, scientific, and technical communication, color input devices will become essential components of image processing, display, and computer systems.

Notes

[1]Using "spectral resolution" for "tonal resolution" or "dynamic range" is formally incorrect, but it has become the standard usage in the field. ■

In memoriam

Eugenio Segredo, who ably served SID as treasurer, secretary, and vice-chairman of the Mid-Atlantic Chapter in good times and bad, died on August 25, 1988. He will be missed by his colleagues at IBM and SID and by all who were fortunate enough to have known him.

Toyo Corporation's new TPG-4300 Full Color Video Printer outperforms the competition hands down.

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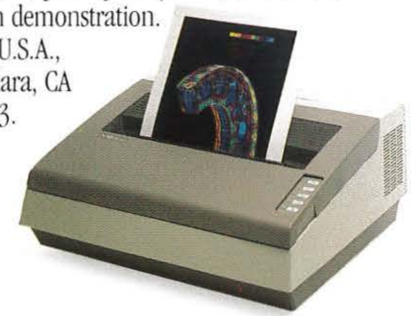

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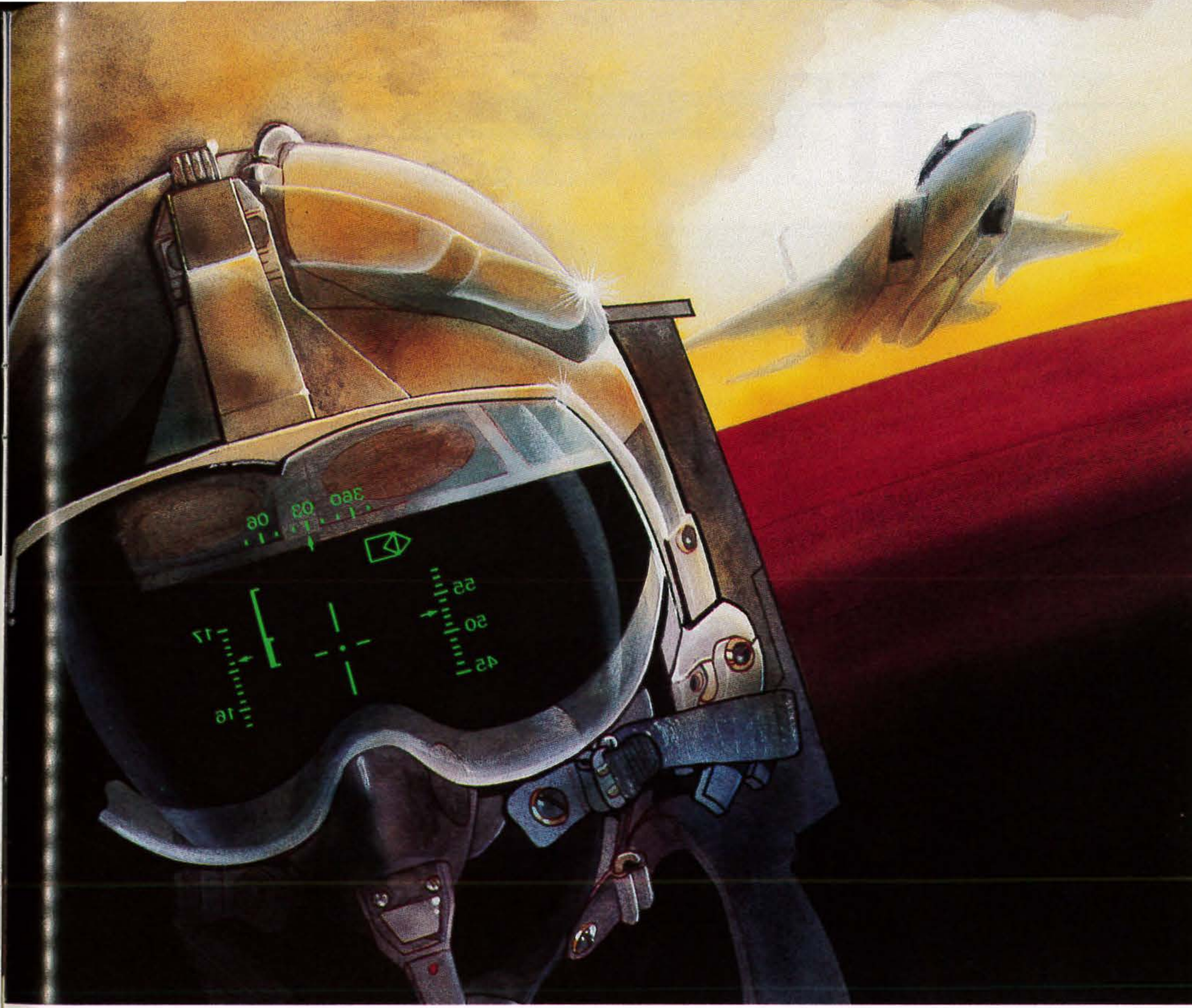

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Input Devices

edited by Sol Sherr
310 pp. San Diego: Academic Press, 1988. $54.95 cloth.

Reviewed by CARLO INFANTE

With the popularization of personal computers and engineering workstations, most of us seem to spend a lot of time pounding away at keyboards, moving a mouse, or spinning a trackball. In other words, we use one or more input devices as part of our work. While many hold strong opinions on the virtues of one input technology versus another, the detailed knowledge of how these devices actually work has been the province of a select few. Even fewer are those cognizant of the results of relevant human factors studies. In this context, a very welcome addition to the technical literature is this slim volume summarizing the state of input-device technology.

Sol Sherr, who is well known to the display community as an author and as the editor of the *Proceedings of the Society for Information Display*, has organized the seven chapters by ten authors into an effective whole.

The introductory chapter by N. S. Caswell (IBM) covers the fundamental principles of interactive input systems, provides the basic models of user/machine interaction, and discusses the fundamentals of ergonomics. Transducers are classified and each category is covered in some detail. Converters—circuits that convert the analog signal from the transducer to a digital value for further processing—are covered next. For both subjects, Caswell discusses the fundamental physics of the situation and provides key equations. In his section on processing primitives, the author discusses techniques used in getting from raw data to the codes useful for a particular application. The chapter concludes with a section on real devices that covers alphanumeric keyboards, light pens, barcode readers, optical scanners, and eye trackers among others.

In Chapter 2, "Human Factors Considerations," L. Arnaut (HP) and J. S. Greenstein (Clemson University) cover the main HF issues related to each technology and present experimental results from the literature together with their recommendations, concluding with an excellent summary table. The obvious expertise of the authors and the thoroughness of their presentation are impressive, but the paucity of experimental HF data is distressing. As an example, performance comparisons between the mouse, the keyboard, and the trackball are discussed thoroughly, yet no mention is made of the fact that certain devices (such as mice) are more suited to those blessed with good coordination. Others who, like the reviewer, are deficient in this area, find trackballs much more useful.

In the excellent chapter on keyboards, Greenstein and W. H. Muto (TI) distinguish between fixed- and variable-function keyboards and list the pros and cons of each. They discuss alternative layouts (QWERTY, Dvorak, and alphabetical) and put to rest a number of myths about them, including the one concerning relative productivity. The authors analyze the layout of numeric keyboards, cursor-control keys, and function keys. One-handed, sequential, and chord keyboards (which require simultaneous pressing of two or more keys) are also covered. Greenstein and Muto go on to examine the mechanics of the various keyboard technologies—mechanical, reed, capacitance, Hall effect, and membrane. Also discussed are life, timing and rollover, tactile and visual/auditory feedback, results of HF experiments, and issues relating to keyboard dimensions. Particularly valuable are their cautions against some common pitfalls in running HF experiments.

In Chapter 4, "Digitizers and Input Tablets," T. Davies, H. Matthews, and P. D. Smith (Summagraphics) do a good job in covering definitions of important terms such as accuracy, resolution, report rate, jitter, etc. They then review the main technologies, concentrating on electromagnetic induction, which is the most popular. They also do not neglect cursors, styli, and 3D digitizers.

Chapter 5 covers the popular technology of the mouse. After an introduction that covers some definitions and history, C. Goy (MSC Technologies) discusses some of the human factors issues. Unfortunately he reveals his bias with the sentence, "These studies invariably conclude that the mouse is faster, more error free, and less fatiguing than the other devices that were tested, and that its advantages are apparent to experienced as well as first-time users." Nonetheless, the author then does a nice job of reviewing the main technical approaches, including mechanical, optomechanical, and optical. The various data types are studied to the level of pinout specifications, and the communication protocols used by companies such as Mouse Systems, Summagraphics, and Microsoft are given.

In the rather short Chapter 6 on trackballs and joysticks, D. Doran (Weston Controls) provides detailed coverage of the mechanical techniques used in displacement and force joysticks, but devotes only one page to trackballs. This is unfortunate because the HF studies cited in Chapter 2 show that trackballs can be the technology of choice in applications such as text editing. Interface and human factors issues are also treated rather summarily.

The last chapter, "Voice Input Systems," is a disappointment. I was looking forward to learning the essential principles of this technology, how some of the many important HF issues are being addressed, and why this technology, described as "just around the corner" for over a decade, has yet to establish a significant presence. Author S. Viglione (Interstate Voice Products) has chosen instead to briefly summarize the elementary physics of speech and then describe a few commercial voice input systems on a block diagram level.

On the whole, this book is extremely informative and well written. Photographs of commercial implementations abound, as do schematics and diagrams. Each chapter provides the reader with an extensive bibliography. Anyone involved in the design of a computer system or wishing to become conversant with the "I" part of the "I/O" equation would be well advised to read *Input Devices*. ■

Carlo Infante is a consultant in the San Francisco area and is well known to the display community. He holds six patents and is the author of several papers including a widely presented tutorial on CRT systems.

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