

how it works

PAPER IS A HUMAN-READABLE STORAGE-AND-DISPLAY TECHNOLOGY THAT REQUIRES NO POWER SOURCE TO OPERATE. CAN ELECTRONIC DEVICES EVER COMPETE WITH THAT?

Does electronic ink mean the end of paper?

By Robert Cravotta, Technical Editor

THE ADVENT OF ELECTRONIC displays fueled the expectation that paper would become obsolete. Has this decades-old vision completely faded away? Contrary to the predictions for a paperless office, more trees are felled each year and pounded into paper than

ever before. Paper cannot match the flexibility to change an image that is characteristic of electronic displays. An electronic display can act, albeit sequentially, as any piece of paper, eliminating the need to substitute one piece of paper for another when information changes. Computer displays have continued to evolve, offering better resolution and contrast, resulting in improved readability. So why hasn't the paperless office become a reality?

The humble paper business card helps illustrate some of the issues facing a paperless office. Electronic business cards are practically free, can be delivered virtually anywhere in the world almost instantly, and are exchanged via e-mail everyday. You can even wirelessly beam them between PDAs. Yet, paper business cards are still exchanged at face-to-face meetings and enclosed in paper mailings. Even after you add them to your electronic address book, you keep and file important paper business cards. Paper is persistent storage that, unlike electronic storage, is largely unaffected by power outages, failed components, virus attacks, obsolete or corrupted storage media, obsolete operating systems, evolving file formats, or even the availability of a computer. Paper is a human-readable storage medium that requires no special equipment, beyond our eyes, or power source to retain or display information.

Even though paper takes up more space, it shines

as an archive-storage technology when compared with electronic storage. Paper is analogous to clay tablets; they are legible even after thousands of years. The remaining challenge is to translate the language. I stored the first programs I ever wrote on punched paper cards and paper tape. If I were to find one of those programs in a box, I could still read or translate the program by hand. However, less than 20 years ago, I stored papers on a cassette tape with a TRS-80. I would be hard-pressed to find a contemporary electronic device or computer that could retrieve those papers from the cassette. My files would be on contemporary equipment if I had actively managed and continuously migrated them to contemporary storage technology. In the case of my cassette tape, it would have minimally required several migrations: Transfer the data to a single-density floppy disk, transfer the data to a PC as ASCII text via the serial port (losing all formatting), add for-

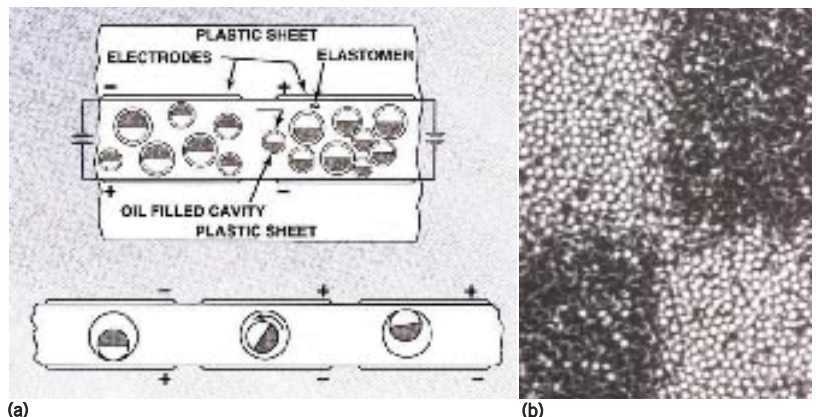


Figure 1

Applying a voltage causes Gyricon's spheres to change color by rotating (a). A magnified view shows the colored halves of the 100-micron spheres (b) (photo courtesy Gyricon Media).

matting back with a PC word-processing program, and migrate the formatted file from one word-processor version to another every few years. It is much easier, faster, and cheaper to take my archived paper copies and scan them into contemporary equipment when I need them.

Looking at paper as a display technology reveals additional advantages over electronic displays. Paper better reflects ambient light, has a wider viewing angle, and is more readable over a larger range of lighting conditions than electronic displays. Paper is ergonomically shaped and supports our innate vision processing, which allows rapid searches for data when placed in a linear array, such as a book. Electronic ink is a young technology that can integrate paper's viewing qualities and approximate paper's no-power-source advantage over electronic devices (see sidebar "It's about power").

ELECTRONICS GET INK

The first electronic ink was demonstrated in 1975 at Xerox's Palo Alto Research Center. This technology uses a thin sheet of transparent, flexible, silicone rubber that is randomly embedded with millions of 100-micron or smaller solid polyethylene spheres that have contrasting colors, such as black and white, on opposite hemispheres and are charged so that they exhibit an electrical dipole. The spheres reside in oil-filled cavities in the sheet and are free to rotate within those cavities. When you place an electric field close to these spheres, it attracts or repels the contrasting colored halves, causing the spheres to rotate and appear to change color (Figure 1). The term *gyricon* describes the rotating characteristic of these spheres, and it is also the name of the company, Gyricon Media, which spun off from Xerox last year to pursue this technology.

A group at the Massachusetts Institute of Technology's Media Lab demonstrated a different ap-

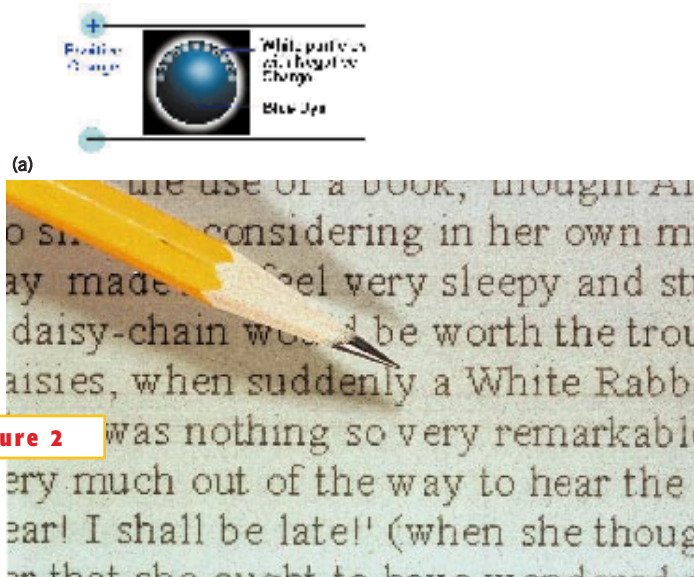


Figure 2

Applying a voltage causes E Ink's capsules to change color by moving pigment chips through colored oil (a). An active-matrix display has a comparable resolution of a laptop monitor (b) (courtesy E Ink Corp).

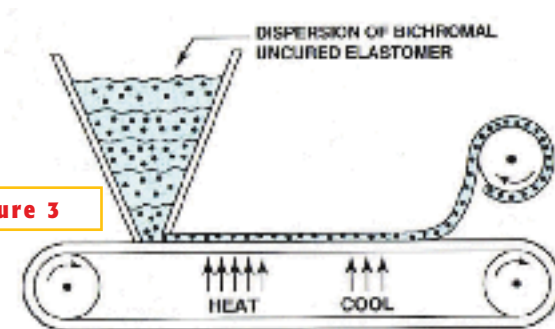


Figure 3

A sheet of electronic paper is produced by curing an extruded mixture of electronic-ink balls and uncured elastomer.

IT'S ABOUT POWER

Power-generation and battery-disposal considerations are relevant in a world in which the number of devices with electronic displays is moving beyond one device per person. Perhaps the most exciting characteristic of electronic paper is that, like traditional pulp paper, it requires no power source to hold an image. You need power only when your task does not require paper, such as changing a stored image. Electronic ink can consume one-tenth the power

of a similarly sized low-power, reflective LCD when used for normal reading applications because images change at a much slower rate than the refresh rate of an LCD. This low-power display technology allows portable devices to use much smaller batteries, making them less expensive and more portable.

The positive impact of electronic ink can be staggering to the power-generation industry if you consider that televisions and

computer monitors in a standby or off state consume power on the order of watts to provide fast display service. Electronic-ink displays require no standby power. Using electronic ink in televisions and monitors may drastically reduce the requirement for millions of watts of standby power.

Wall-sized electronic paper for use in homes and offices is financially feasible because electronic ink requires no power to hold an image, and images can

remain intact without refresh for many weeks. A less fanciful and more immediately available application is for signs and price tags in retail establishments (\$14 billion annually for in-store media, according to Veronis, Suhler, and Associates). You can significantly reduce the material and labor required to change shelf tags along with the added benefit of more price accuracy between the shelving display and the point-of-sale equipment.

proach to electronic ink in the mid-1990s. The group shortly afterward founded E Ink Corp to pursue applications with its approach to electronic ink. Similar to Gyricon's approach, E Ink's technique uses a thin sheet of rubber that is embedded with similarly sized hollow capsules that are filled with colored oil and small, electrically charged chips of pigment that contrast with the oil. Rather than rotating when a voltage is applied near the capsules, the pigment chips are electrically attracted or repulsed between the front and back of the capsule (Figure 2). The colored oil obscures the pigment chips, making them invisible when they are pushed to the back of the capsules.

Despite the different implementations, both technologies share similar viewing characteristics, and both work on the same principle of using localized voltages of 15 to 125V to create and change observed images. Average power consumption can be less than one-tenth the power that a low-power, reflective-LCD screen of a similar size requires when used for normal reading. Electronic ink currently can display at a 100-dpi resolution, which is a little better than a PDA display. As a reflective-display technology, electronic ink has similar optical properties to ink on paper, such as a wide viewing angle, lack of glare, and readability in ambient light without the need for backlighting that emissive displays can require. Unlike emissive displays, reflective images do not "wash out" in fluorescent or bright lighting. A reader does not experience "refresh fatigue," which is possible with emissive displays, because refreshes occur only when you change the displayed image. In ongoing tests, electronic ink has performed more than 5 million refreshes without malfunctions or fading.

HOW TO DRAW IMAGES

Manufactured sheets of raw electronic paper measure $\frac{1}{10}$ in. thick, are flexible enough to wind around a cylinder like rolls of paper, and can be coated onto almost any surface (Figure 3). Raw electronic paper is a passive device that you can use in a fashion similar to pulp paper. Images imprinted on it are not noticeably susceptible to corruption from gravity or shaking; however, if electronic ink is not within a protective housing, it is susceptible to unintended image changes from electric fields placed near it. Housing electronic paper permits you to address the sheet and use it as an active display. A variety of approaches to imprint images exists, each with different flexibility and cost factors.

You can imprint electronic paper with images by passing it through a printer device or by waving a wand that contains a single row of transistors over it (Figure 4). To change the image, you need to run the paper through the printer or pass the wand over it again. These two approaches are the least expen-



Figure 4

Passive electronic paper and a linear array that addresses devices like a wand or a printer deliver a reusable display that acts like paper (courtesy Gyricon Media).



Figure 5

A 5x5-in. prototype of a flexible, active matrix addresses an electronic-ink display (courtesy E Ink Corp).

sive because the addressing circuitry is not integrated into the paper but at the expense of the paper's inability to perform automated image updates.

Integrating addressing circuitry with the paper results in an active device that can update itself without manual manipulation of the paper and an addressing device. In the least expensive option, the backplane contains several preprogrammed, fixed images or messages. Alternatively, the backplane can contain circuitry that addresses and controls an array of individual pixels. Passive-matrix addressing, in which pixels are turned on or off using one transistor for each row and column, is insufficient for high-resolution images. Active-matrix addressing, which LCD screens also use, uses a separate transistor for each pixel, which drives up the cost of production and limits the practical size of the paper. Currently, using a backplane means the paper is rigid and loses one of the big advantages of paper: the ability to bend.

E Ink and Lucent Technologies are developing flexible active-matrix-display techniques. The approach uses organic-transistors and rubber-stamp-lithography processes to place addressing circuitry onto a sheet of transparent Mylar. A display consists of two thin sheets of plastic, one with printed or-

ganic transistors and electronic ink on the other. The sheets are laminated together. A prototype for a flexible display is 5×5 in. and contains 256 pixels (Figure 5).

EVOLUTIONARY ISSUES

Electronic ink as a display technology is still in its infancy and is likely to go through an evolution of color depth, resolution, and refresh rates as emissive displays continue to do. The manufacturing processes still have room to improve temperature and vacuum processes to improve the color depth, resolution, and refresh rates that are currently insufficient for video applications. Fortunately, it is possible to cross the road to becoming video-ready.

Current electronic-ink displays are not limited to just black and white but are limited to two colors due to the bichromal characteristic of both electronic-ink implementations (Figure 6). However, if you use lower and shorter electrical pulses, the result is the visibility of a mixture of the two contrasting colors. Electronic ink can display a few shades between those colors, such as several pinks on a red-and-white display. Displays that can exhibit more than two base colors should be available if you migrate to subtractive coloring using CMY filters and extend the techniques for displaying shades between two colors.

The addressing implementation is not the technical limiting factor for displaying at higher resolutions. Transistors that are lower performance than the transistors that LCDs currently use are sufficient to drive recently demonstrated high-resolution electronic paper. Increasing the resolution of electronic ink requires further refinement in the manufacturing process to make smaller balls and increase the packing density.

The current refresh rate of electronic ink is acceptable at less than 10 Hz. Lower refresh rates result in sharper and higher contrast images, whereas higher refresh rates have noticeably lower sharpness and contrast. The viscosity of the oil you use as well as the voltage level you use in either implementation affect the refresh rate. Lower-viscosity oils permit faster transitions but face evaporation issues. Higher voltages mean faster and sharper transitions, which conflicts with using lower voltages to get more shades of a color. Manufacturing and addressing refinements have to accommodate these trade-offs as the technology continues to mature.

Until electronic storage can address inexpensive and reliable data protection, deliver continuous data accessibility, and guarantee future content/browser compatibility, humble pulp paper will continue to be a strong choice as an archive-storage material. Issues of durability, reliability, resolution, and low refresh rate still exist. However, electronic ink exhibits low power consumption, superior viewability over



Figure 6

The colors are demonstrated as electronic ink (courtesy Gyricon Media).

emissive displays, and the ability to be configured over and over and coated onto almost any surface. These features make electronic ink a display technology that could some day replace short-life paper applications and traditional emissive displays for appliance control, computing, and entertainment. □

AUTHOR'S BIOGRAPHY

Technical Editor Robert Cravotta developed assemblers and compilers in the early 1980s. Graphical debugging and data visualization has changed a lot from the days of the text-line-console output.



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