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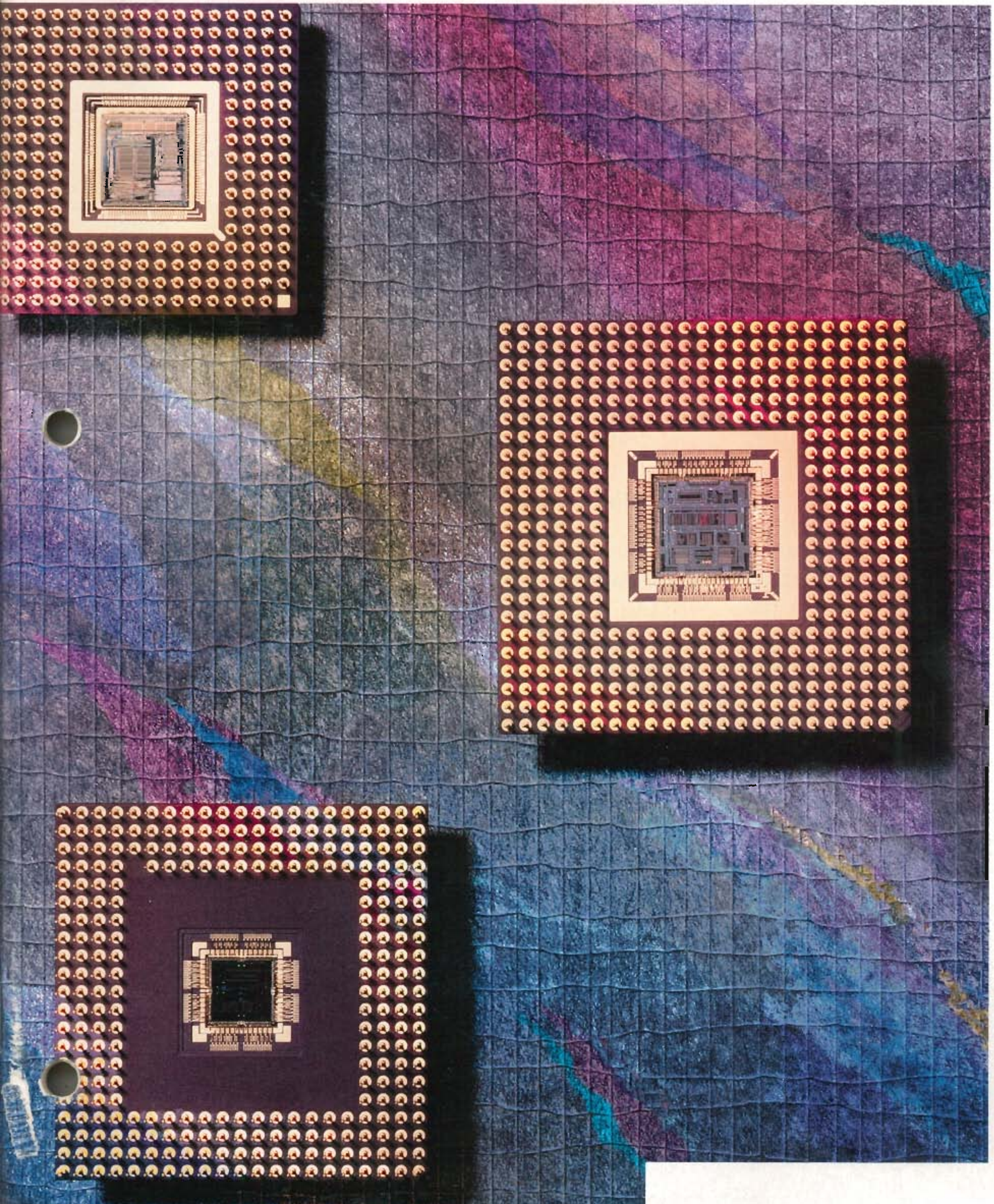

HEWLETT PACKARD

Low-Cost Plain-Paper Color Inkjet Printing

The HP DeskWriter C and DeskJet 500C printers are based on advanced thermal inkjet technology in the form of a 300-dpi three-color inkjet print cartridge. The printers and software drivers that use this cartridge were developed on an aggressive one-year schedule.

by Daniel A. Kearl and Michael S. Ard

The use of color in written communications has revolutionized the printed-output industry. The ability of vivid colors to draw attention and stimulate retention is immense. High-density color monitors and high-quality color applications for personal computers have reset customer expectations. However, an affordable, plain-paper color printing solution has not been available.

The introduction of the HP DeskWriter C printer in the summer of 1991, followed by the HP DeskJet 500C printer, set new standards for low-cost color printing.[1,2] At the heart of these printing solutions is HP's three-color 300-dpi thermal inkjet print cartridge. This print cartridge provides the printer with the ability to deliver high-quality 300-dpi color images and graphics on a wide variety of "plain" office papers. This 300-dpi plain-paper color capability represents a major increase in price/performance for personal printers. It is a good example of a technology-enabled performance increase. Fig. 1 shows the HP DeskWriter C and DeskJet 500C printers and Fig. 2 shows examples of their output.

Color Print Cartridge

The color print cartridge for the HP DeskJet 500C and DeskWriter C printers is another extension of HP's thermal inkjet printing technology (see "Thermal Inkjet Review...," page 67 and references 3, 4, and 5). This technology was first made available in 1984 with the introduction of the HP ThinkJet line of printers. These printers initially used a black print cartridge that had 96-dpi resolution and required special paper. Later enhancements brought plain-paper and single-color printing to the personal printer user. In 1987 HP introduced the HP PaintJet series of printers. These printers provided a fully integrated color printing capability on special paper at 180-dpi resolution. The price and performance of the HP PaintJet printers represented a significant advance at the time of their introduction. The HP DeskJet line of printers was introduced in 1988. These printers offered high-quality 300-dpi black printing on a wide variety of office paper types. As noted above, the color-capable versions of the DeskJet family were introduced in the latter part of

Fig. 1. HP DeskWriter C and DeskJet 500C color thermal inkjet printers.

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Fig. 2. Examples of HP DeskWriter C and DeskJet 500C printed output.

1991, the HP DeskWriter C printer for Macintosh computers and the HP DeskJet 500C for the PC. Print cartridge technology development has played a critical role in the successful introduction of each of these generations of thermal inkjet printers.

Reduced to the simplest terms, the HP DeskJet 500C/DeskWriter C color print cartridge is a compact, low-cost, high-resolution color dot generator. The printer dictates to the print cartridge when and where to deliver the color dots. This particular cartridge delivers three different colors of dots: cyan, yellow and magenta. These colors are known as subtractive primary colors. The size, shape, and optical properties of the dots produced should ideally be independent of the media and the printing environment. These dots should be delivered to the media at a very high rate of speed with a positional accuracy commensurate with the high resolution of the device. All of the dot generator properties should remain constant over the storage and printing life of the print cartridge. These relatively simple color dot generator performance goals represented a major development challenge for the HP Inkjet Components Division.

In outward appearance, the color print cartridge for the HP DeskJet 500C and DeskWriter C printers is very similar to the original HP DeskJet black print cartridge (Fig. 3). The plastic body of the print cartridge has been enlarged somewhat to provide room for the three individual ink reservoirs. Electrical interconnection to the printer is accomplished using the same flex circuit technology as the black print cartridge. The location of the pressure interconnection pads is identical to those on the black print cartridge. Provisions have been made in the printer drive electronics to sense which cartridge has been installed and respond with the appropriate drive signals.

In general, the thermal inkjet drop generator portion of the color print cartridge for the HP DeskJet 500C and DeskWriter C represents a natural extension of the existing HP DeskJet black print cartridge technology. Careful inspection of the gold-plated nickel nozzle assembly shows that the nozzles have been arranged into three groups or *primitives*, one for each of the subtractive primary colors (Fig. 4). The three primitives all share a common silicon thin-film substrate and circuitry. This thin-film substrate is fabricated using processes very similar to those used for the HP DeskJet black and HP PaintJet print cartridges.[3,4] The primitives are staggered with respect to one another to provide separation for the ink delivery channels on the back side of the substrate. Each of the primitives consists of two columns of eight nozzles each. The nozzles within a given column are spaced on 1/150-inch centers. Each column in a given primitive is offset with respect to its neighbor by 1/300 inch, so that the combination of the two nozzle columns results in an array of 16 nozzles with a vertical resolution of 1/300 inch.

The major technology contributions in this color print cartridge are in the areas of ink chemistry and manufacturing processes. Ink formulation is the key to producing high-quality plain-paper color images and graphics. A discussion of the nature of plain paper has been presented in an earlier

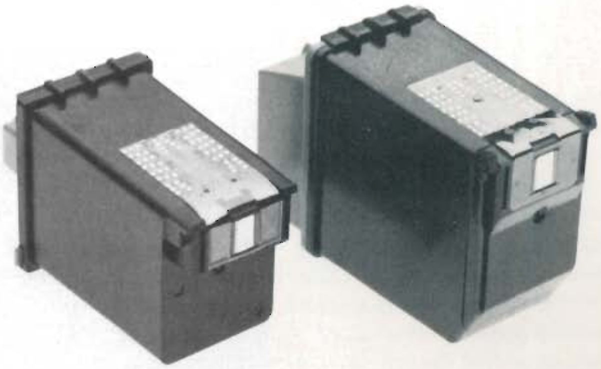

Fig. 3. The original HP DeskWriter/DeskJet 500 black print cartridge (l) and the new three-color HP DeskWriter C/DeskJet 500C 300-dpi print cartridge (r).

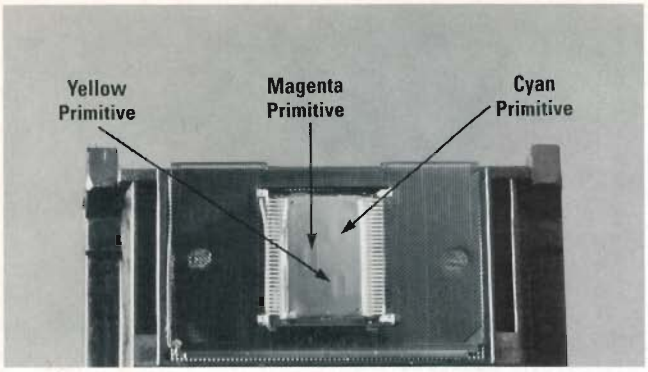

Fig. 4. The nozzles of the three-color print cartridge are arranged in three groups or *primitives*. Each primitive prints one of the three primary colors: cyan, magenta, and yellow.

issue of this publication.[6] The very substantial plain-paper color ink formula development effort is the subject of the article "Ink and Print Cartidge Development for the HP DeskJet 500C/DeskWriter C Printer Family," which follows this article. Several challenges unique to color printing were met in this ink development project.

The additional complexity of three independent ink reservoirs presented substantial challenges in the print cartridge manufacturing area as well. These challenges are discussed in three articles. The first, "Automated Assembly of the HP DeskJet 500C/DeskWriter C Color Print Cartridge" (page 77) provides insight into several of the problems of high-volume manufacturing of this three-color thermal inkjet device. Machine vision is extensively used in these manufacturing operations, and is the topic of the article "Machine Vision in Color Print Cartridge Production" on page 87. Finally, the demanding applications of adhesives technology are discussed in the article "Adhesive Material and Equipment Selection for the HP DeskJet 500C/DeskWriter C Color Print Cartidge" on page 84.

Fast-Track, Leveraged Product Development

The HP DeskWriter C and DeskJet 500C printer designs were leveraged from the successful HP DeskWriter and DeskJet 500 printers, both high-quality 300-dpi monochrome products. Leveraging from successful products still required enormous effort to deliver color printing solutions to market in approximately one year. Prioritized and focused program execution by all departments and functional areas was critical in accomplishing the following major steps in this aggressive development program.

First, there was an immediate focus on key feature-set requirements and crucial program objectives. The urgent market opportunity drove the schedule as the primary objective. Early customer research in the form of extensive phone screening and user focus groups provided important data on required features, applications, and pricing. Usability studies were also conducted to verify the acceptability of a one-cartridge color-printing solution in terms of both ease of use and throughput performance. With this data, the product team identified the critical market "must" features, leaving the balance of design opportunities for future product revisions or new product developments. This research data also facilitated trade-offs required late in the development stages to meet aggressive schedule objectives.

Next, there was intense execution of the program objectives by the development staff. Participating on a leading-edge product with such apparent potential provided great team motivation. At the heart of this team effort was an experienced core of engineers whose insights and awareness were invaluable in making real-time design decisions and trade-offs to support a market-driven schedule. The product development teams were organized into two primary groups: printer-product and environment-driver development. Printer-product development consisted of a mechanical team and an electronic and firmware team. Environment-driver development included a Macintosh driver team and a Microsoft® Windows driver team.

Each development group faced significant design issues. The printer-product group focused on supporting the new color and monochrome print cartridges. The mechanical team focused on physical pen support, including carriage mounting, movement, electronic interconnect, service and storage of the print cartridges, plus enhanced media flexibility and support. The electronic and firmware team pursued development of color support algorithms and logic. These required key architectural enhancements and additions, plus complex host interaction and task partitioning.

The environment-driver group supported the majority of the color science requirements, including intelligent formatting, rasterizing, color matching and dithering algorithms for optimum output results (see "HP DeskWriter C Printer Driver Development," page 93). The contribution of the environment drivers in providing an extensive, high-quality, color-optimized solution was of major significance. An example of this is the printers' support of over sixteen million unique colors based on 24-bit color data. The drivers also provide ways to overcome limitations of the printhead and ink technologies. An example is the extension of the environmental print range by providing user-adjustable intensity or ink depletion settings for the output.

Because of the tight schedule, the development activities tended to parallel standard textbook approaches to fast-track product development. There was a clear market focus, clearly defined program objectives, a firm product definition, total site commitment to the development effort, experienced development and management teams, process flexibility, and significant leverage opportunity. Unique to this product development were several activities that had significant impact on minimizing schedule and reducing design risk.

First, the HP DeskWriter C printer for the Macintosh environment was targeted for initial introduction, with the DeskJet 500C for the PC market offset by two months. This allowed initial attention to be focused on the Macintosh environment solution. Key developments and insights from the Macintosh printer and driver were then leveraged and applied to the PC environment printer and the Microsoft Windows driver.

Next, effort was made to ensure that ample engineering resources were available for this fast-track program, especially on the mechanical team. This provided flexibility to move development resources where they were most urgently needed, when they were needed. Understaffing fast-track development projects is a major failure risk.

(continued on page 68)

Thermal Inkjet Review, or How Do Dots Get from the Pen to the Page?

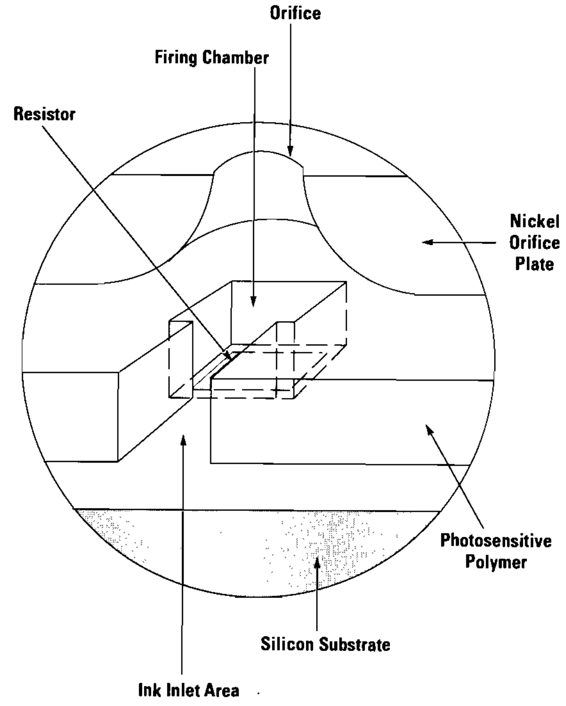

Fig. 1. An exploded cross-sectional view of a single inkjet nozzle.

The print cartridge for the HP DeskJet 500C/DeskWriter C printers delivers dots to the page using thermal inkjet technology. The fundamental technology is the same as that used in previous Hewlett-Packard inkjet products such as the HP ThinkJet, PaintJet, and DeskJet printers. Detailed descriptions of these products[1-4] and more in-depth discussions of thermal inkjet theory and background[1,5] can be found in the literature.

In its simplest form, an inkjet device consists of a tiny resistor aligned directly below an exit orifice. Ink is allowed to flow into the resistor area, and when the resistor is heated, the ink on the resistor essentially boils and forces a tiny droplet of ink out of the aligned orifice. This is called *firing* the nozzle.

A cross-sectional view of a single inkjet nozzle is shown in Fig. 1. On the floor of the firing chamber is a resistor. This resistor is patterned onto a silicon substrate using conventional thin-film fabrication procedures. Leads are connected to the resistor through the thin-film substrate. These leads ultimately travel out to the flexible circuit on the body of the print cartridge, through which a voltage can be applied across the resistor. The resistor is the heart of the thermal inkjet device and the size of the resistor is the primary factor governing the volume of the ejected droplets.

The walls of the firing chamber are made up of a photosensitive polymer. This polymer serves to define the walls of the firing chamber and determines the spacing between the resistor surface and the orifice. The thickness of this photosensitive barrier and the dimensions of the firing chamber are critical to the production of a well-formed droplet.

The photosensitive polymer also defines the dimensions of the inlet area to the firing chamber. Ink enters into the firing chamber through this inlet area. Like the barrier thickness, the inlet dimensions greatly affect the characteristics of the ejected droplet.

Finally, a gold-plated nickel orifice plate sits on top of the barrier. An orifice is formed in this plate directly above the firing chamber. This orifice hole is formed using an electroforming process. The diameter of the orifice has a direct bearing on the volume and velocity of the ejected droplets.

To fire a drop, a voltage pulse is applied across the resistor. This pulse is typically very short, on the order of 2 to 5 microseconds in duration. The voltage pulse causes the resistor to heat up, temporarily bringing the resistor surface to temperatures up to 400°C. Heat from the resistor causes ink at the resistor surface to superheat and form a vapor bubble. Formation of this vapor bubble is a fast and powerful event and expansion of the bubble forces some of the ink in the firing chamber out of the orifice at velocities of typically 10 meters per second.

By the time a droplet is ejected, the resistor has cooled down and the vapor bubble has collapsed. Through capillary forces, more ink flows into the firing chamber through the inlet area, thus readying the system for the firing of another droplet. The frequency at which the printhead can repeatedly fire droplets is determined by several factors including the inlet dimensions, the barrier thickness, and the fluid properties of the ink.

The device described above is essentially a droplet generator. The device designer has a fair amount of control over the characteristics of the ejected droplets. For example, the volume of the ejected droplet can be controlled by changing the size of the resistor—bigger resistors give droplets of larger volumes. In addition, the diameter of the orifice can be used to control droplet volumes. Droplet velocity is also controlled primarily by the diameter of the orifice.

The frequency at which droplets are ejected can be controlled by altering the size and shape of the barrier and by changing the rheological properties of the ink. For the particular design chosen for the HP DeskJet 500C/DeskWriter C printhead, and for the ink fluid characteristics, the typical operating frequency of the printhead is about 3 kHz.

Droplet characteristics, as they relate to print quality on the media surface, can be optimized through careful control of orifice profiles and resistor/orifice alignment. Ink, which also has a dominant effect on print quality, is discussed in more detail in the article on page 69. Ink properties such as surface tension, viscosity, and thermal stability all play important roles in the production of useful droplets.

In real-life inkjet printheads, multiple nozzles are lined up on a single silicon substrate/orifice plate assembly to form an array of droplet generators. Fig. 4 on page 66 shows the layout of nozzles for the HP DeskJet 500C/DeskWriter C print cartridge. These nozzles can be fired in rapid succession as the printhead is scanned across a sheet of paper or other media. The firing of these multiple nozzles at high frequencies under control of a microprocessor can produce high-resolution, high-quality text and color graphics at scan rates of 10 to 20 inches per second. Thus we see that thermal inkjet technology offers a compact, highly tunable method for delivering droplets from the pen to the page.

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A substantial and thorough testing effort was put in place early in the program. Specific and tailored test processes covered both the printer-product and the environment-driver developments. This investment allowed early identification of design defects and concerns. Where changes were required, early identification enabled easier and more cost-effective solutions while minimizing schedule impact.

Aggressive schedules were broken into short development-based milestones. This allowed close monitoring of progress, and kept all developmental activities visible. Issues and concerns were monitored at the program level on a weekly basis to ensure that problems were addressed and resolved expeditiously.

Finally, frequent prototyping throughout the development cycle allowed immediate evaluation of design solutions. Prototype builds in large numbers provided printer units to facilitate all cross-functional development, testing, and extended support activities. To meet fast-track, aggressive schedules, an organization must be willing to spend money—especially on prototypes in sufficient quantities to meet a large demand. Outstanding support by manufacturing and the model shop in this regard was crucial. Similarly, early availability of print cartridges in large quantities was essential to keeping fast-paced development activities on schedule throughout the design, implementation, and test cycles.

Acknowledgments

The success of these products can be attributed to the major development efforts and cooperation of two HP divisions: the Inkjet Components Division (ICD) in Corvallis, Oregon, and the Vancouver, Washington Division (VCD). ICD developed the color printing technology in the form of a new color cartridge containing high-resolution, plain-paper inks. VCD adapted this technology to printer products and host environments to produce total system solutions via fast-track, leveraged product development. Special assistance was also rendered by HP Laboratories and the San Diego Printer Operation (SPR).

The dedicated support, direction, and cooperation of division and functional management from ICD and VCD was a prime factor in the success of this program. Recognition and appreciation go to the program management staff, including Bob McClung, Ron Prevost, and Tom Braun. The contributions of other management staff and their respective organizations were significant, particularly those of John DiVittorio, Gary Cutler, Dan Weeks, Joe McGuckin, John Coyier, Melissa Boyd, and Bob Conder. There were also numerous individual contributors whose efforts, accomplishments, and personal sacrifices were key in this most aggressive program undertaking.

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Ink and Print Cartridge Development for the HP DeskJet 500C/DeskWriter C Printer Family

A new trichamber print cartridge allows the low-cost HP DeskJet printer platform to print in color. The ink vehicle, dyes, dye concentrations, and interactions had to be carefully traded off to optimize performance with respect to color bleed, color saturation, composite black production, edge acuity, drying time, and resistance to crusting.

by Craig Maze, Loren E. Johnson, Daniel A. Kearl, and James P. Shields

Development of the print cartridge for the HP DeskJet 500C and DeskWriter C printers required a combination of ink chemists, print cartridge architects, and design engineers, along with inputs from the fields of color science and product marketing. This article deals with the design and development of the inks and the print cartridge.

The major objective of the printer development project was to provide a low-cost desktop printer that produces laser-quality black print and also offers color capability to the user. To enable the low-cost HP DeskJet printer platform to print in color, a trichamber color print cartridge was designed that can be exchanged for the black print cartridge when color printing is desired.

Incorporating a trichamber color print cartridge into the existing HP DeskJet print platform posed several challenges for ink chemistry and print cartridge design. Like the ink for the black-only HP DeskJet printer family, the color inks had to work on a wide variety of "plain" papers. Plain paper printing using thermal inkjet technology has been reviewed.[1] One important consideration is ink drying time. In addition, when inks of different colors are laid down next to one another on the paper, they must not bleed or diffuse into adjacent regions of different color, a fault commonly referred to as color bleed. A significant level of color bleed is undesirable and causes the border between the two colors to appear ragged and undefined.

Another challenge involved the production of composite black. This term refers to the production of black using the three primary colors (cyan, yellow, and magenta) from the trichamber print cartridge. Composite black results from printing dots of cyan, yellow, and magenta directly on top of each other. This requirement exists because only the black print cartridge or the color print cartridge can reside in the printer stall at any given time. Thus, when the color cartridge is installed, any black print must be produced using composite black. As discussed later, this required some trade-offs between the composite black color characteristics, the color quality of the primary and secondary colors, and ink robustness.

Finally, the greatest challenge was perhaps in the development of an ink that performed well on a wide variety of plain papers. These paper types range from high-quality cotton bond papers to the papers used in high-speed copiers. Finding an ink that met all of the challenges involved delicate trade-offs among objectives that were often in conflict.

Evolution of the Ink Vehicle

Water-based color inks have evolved from formulations designed to print on special paper to those capable of printing on plain paper. Many hundreds of different mixtures were tried before obtaining satisfactory performance over a large variety of papers. In general, inks changed from those containing large amounts of diethylene glycol, about 60%, to those containing different organic solvents at greatly lowered concentrations.

Some of the requirements on the ink are in conflict. For example, drying must be slow in the print cartridge to prevent plugging of orifices and the associated loss of print quality, but rapid on paper to facilitate paper handling and maintain printing speed. Color bleed, if too great, will ruin a print sample (see Fig. 1). It is also one of the most difficult parameters to control by ink formulation alone. Composite black

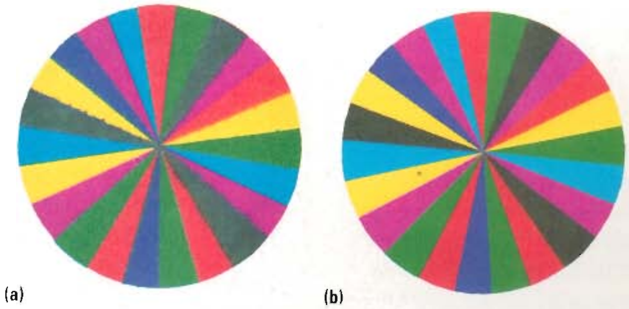

Fig. 1. Color bleed is the undesirable mixing of two colors printed next to each other. (a) Unacceptable color bleed. (b) Minimal color bleed.

text print quality must be high, which means a dark composite black and high edge acuity. Unfortunately, ink formulas that give improved text print quality tend to have increased amounts of color bleed.

It is difficult to meet all of these requirements, and some compromise is unavoidable. Market surveys were used to separate performance factors that are important to our customers from those that matter least. Samples were printed with known defects on different papers over a range of temperature and humidity conditions and with different inks. These were submitted to potential customers for their evaluation and the results were used to guide ink development. For example, high color saturation was a strong customer requirement, and ink component concentrations were adjusted accordingly.

The first major challenge was to provide a formulation that would not bleed and would deliver saturated colors. Bleed was suppressed by adding surface-active reagents to speed penetration of the ink into the paper. This reduces the time available for dyes to diffuse on the paper and for colors to mix. Unfortunately, penetration into the paper reduces color saturation, so allowances were made to keep color saturation high.

High-quality composite black text print requires a dark black with high character edge definition. The former is achieved by keeping the dye on the surface of the paper, and the latter by minimizing penetration of the ink into the paper. These requirements can be at variance with factors that control bleed.

It became apparent that to deal with the various trade-offs in an efficient manner a different experimental approach was needed. After some exploratory work, these trade-offs were dealt with all at once by conducting a series of designed mixture experiments. Optimum component concentrations were obtained that achieved acceptable bleed control, color gamut, edge acuity, and color saturation. In general, solvent concentration was kept low, surface tension was reduced, and viscosity behavior modified.

Dye Selection Criteria

In selecting and using the dyes for the HP DeskJet 500C/DeskWriter C color print cartridge, four primary attributes were considered. Any dye to be considered for use had to address all four of the following concerns.

The first performance parameter is resistance to crusting of the ink (nozzle clogging upon loss of vehicle). This parameter was tested by allowing print cartridges to sit uncapped for various lengths of time and then firing them and looking for lost nozzles.

Several characteristics of a dye determine how resistant it will be to crusting. The purity of the dye plays a very important role. The presence of any diluents, reaction by-products, secondary colors, or unreacted feedstocks can degrade crusting performance. As a consequence, some initial effort was expended in cleaning up the dyes that looked promising so that crusting performance could be reliably evaluated.

The structure of the dye also plays a very important role in the crusting performance of an ink. As a nozzle sits uncapped, exposed to the air, the more volatile components of the ink evaporate. The solubility of the dye in the resultant evaporated ink at the nozzle influences crusting performance. This solubility is determined in part by the structure of the dye and its counterions.* Dyes that exhibited crusting problems because of their structure were eliminated from further consideration.

The counterion used to balance the charge on the dye molecule also effects the crusting performance of the dye. In many instances this counterion can be changed to improve crusting performance. For dyes that showed good performance in other respects, the counterion was altered to maximize crusting performance.

A property of thermal inkjet performance called "kogation" (from the Japanese *kogasu*, to scorch) is the second primary attribute that is important to dye selection. Kogation occurs when the ink, which contains the dye, is exposed to the high temperatures generated on the printhead resistor surface during operation. These high temperatures sometimes break down the dye into insoluble fragments that stick to the resistor surface. Alternatively, the dye itself can be bound to the surface. The buildup of this carbonaceous layer on the resistor reduces heat transfer to the ink. In severe cases the print cartridge will no longer fire because of the insulating character of the kogation.

Dyes are tested for kogation performance by firing inks containing the dyes to be tested from a print cartridge. As the print cartridge is fired the volume of the ejected drops is monitored. The presence of kogation tends to reduce the drop volume over the life of the print cartridge, resulting in degraded print performance.

Structure and counterion play a role in dye kogation. Dyes that exhibited poor kogation characteristics because of their structure were discarded. In some cases, kogation can be improved by altering the counterion attached to the dye.

The third primary attribute used for dye selection is the color characteristics of the dye. Hue and chroma are parameters of utmost importance to a color printer. Dyes were chosen to have hues within a given range so that a balanced palette could be generated. Dyes were selected to have the highest chroma characteristics possible.

Finally, given that the dyes must function in a trichambered print cartridge, where the same nozzle plate is shared by the three different primary colors, dye-to-dye interactions had to be considered. A dye must not react adversely with any other dye used in the ink set. Examples of such reactions are precipitation and hue change.

Color Balancing and Dye Concentration Adjustment

Once a set of dyes was selected using the above criteria, the concentrations were adjusted to give good secondary and primary hues and to achieve maximum saturation. These two goals had to be achieved without sacrificing the robustness of the print cartridge performance.

(continued on page 73)

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* Solutions must be electrically neutral. A counterion is an ion that balances out the charge of another ion in solution, that is, its charge is the opposite of that of the ion in question. Thus, for example, a negatively charged dye molecule might have a positively charged sodium ion as its counterion.

Color Science in Three-Color Inkjet Print Cartridge Development

During the development of the three-chamber color print cartridge there was a need to describe and measure the colors that were printed. There are a number of different ways to describe colors. The purpose of this article is to explain how colors are generated with the color print cartridge, what color means, how colors are measured, and how color measurement can be used in print cartridge development.

How the Color Print Cartridge Prints Colors

The print cartridge has three different inks: cyan, yellow, and magenta (CYM). Eight colors can be generated at 300-dpi (dots per inch) resolution by printing different combinations of the primary inks. The eight colors are printed as follows:

- Not printing any ink gives "white," the paper color.
- Printing one of the primaries gives cyan (a greenish blue), yellow, or magenta (a bluish red).
- Printing a combination of two primaries gives the secondary colors, which are red (a mix of yellow and magenta), green (a mix of cyan and yellow), and blue (a mix of cyan and magenta).
- Printing all three primaries gives the tertiary color black.

Note that the various colors are defined by the printing process, so the names given to them here (red, blue, etc.) are not necessarily accurate.

More Colors with Halftoning

To obtain a larger number of colors using the print cartridge, the ratio of the CYM proportions must be changed. This is not possible at 300 dpi because the HP DeskJet 500C is a binary printer. Halftoning algorithms are used to increase the number of printable colors. Each picture element is composed of a number of dots of ink (pixels). In a simple case, each picture element is composed of 4 pixels in a 2-by-2 halftone cell (sometimes called a superpixel). This yields an effective resolution of 150 dpi. Process yellow is now 4 drops of yellow ink in the 4 pixels, 1 drop per pixel. Process red is 4 drops of yellow and 4 drops of magenta, 1 drop of each ink in each pixel. By reducing the number of magenta drops to 3, 2, or 1, three more colors can be produced between yellow and red. This process can be extended to larger halftone cells to increase the number of available colors. There are many different halftone algorithms which yield different colors and textures but all have the ability to increase the number of colors at the expense of resolution. For all these print methods, any color available to the HP DeskJet 500C printer can be produced by specifying how much of the CYM inks to print and where to place the inks. This leads to the concept of a process color space.

Process Color Space

As stated earlier, any color achievable with the color print cartridge can be described in terms of the amounts of CYM being printed for a particular halftone cell. This is an efficient color space for the printer but is not useful for describing the printed color. The problem with process spaces, in general, is that they are system dependent. All printers have the same process color space—the proportions of CYM being printed. Unfortunately, the color printed is not constant, because different printers have different CYM inks. This was apparent in developing the inks for the HP DeskJet 500C print cartridge. Different dyes and vehicles were formulated, all yielding different colors upon printing. A better description of color other than the process space was needed.

Visually Based Color Spaces

Visually based color spaces or color order systems are created by empirically arranging a set of colors according to the observed relationships between adjacent colors. The criteria describing the relationship can be varied, yielding different color systems. Color order systems are all three-dimensional, independent of the sorting criteria. These spaces are very useful because the colors are "uniformly" spaced and based on human perception. A unique value can be placed on any color by visually matching the sample color to an example from a standard color order system.

A widely used color order system is the Munsell notation. Colors are described by:

- Value, a measure of darkness and lightness
- Hue, the shade of the color
- Chroma, the "brilliance" of the color.

This three-dimensional color space has cylindrical coordinates: value is the z axis, chroma is the radial distance, and hue is the angle. It is a satisfying color coordinate system for describing colors because it arose from an empirical sorting of colors into a standard set. The Munsell color space is a uniform color space but has problems in day-to-day use. To use this color order system, a visual comparison between the sample color and the standards has to be made. This is prone to errors and is time-consuming, and the exact standard required must be available.

Measurement-Based Color Systems

The optimal system would be a measurement system that yields values that correlate with a color order system. This has been achieved using the CIE color measuring system.

For a particular observer and illuminant, colors can be uniquely described by three coordinates. Therefore, to measure colors, three values need to be obtained. A one-to-one mapping between the three measurement values and a visually based color space must exist for the measurements to be truly useful.

Three components are necessary for color measurement:

- A light that illuminates the sample
- A sample that has a characteristic reflectance spectrum that changes the relative spectral distribution of the light source
- An observer that detects the reflected light.

Common standard light sources are D65, a representation of daylight, A, representing incandescent light, and F2 or CWF, representing "cool white fluorescent" lights. Standard detectors include the CIE 2-degree and 10-degree observers. At HP we have typically used the D65 source and the 10-degree observer. This source and observer have been selected and standardized to give the CIE system of color measurement.

The CIE system applied to a reflectance spectrum yields X, Y, and Z tristimulus values. These values can be used to specify any color for a given observer and source. Unfortunately, the mapping of the XYZ space onto a visually based color space such as the Munsell space is very nonlinear. Many transformations of the XYZ space were investigated to yield a uniform measurement space. A common transformation is the CIELAB color space. The coordinates of this space, called L^* a^*, and b^*, map quite well into the Munsell space except that a rectangular coordinate system is used to describe the colors rather than a cylindrical coordinate system, as shown in Fig. 1.

Color Measurement

Once the source and the observer are specified, the reflectance spectrum of the sample determines the measured color. In developing the color print cartridge, the reflectance spectrum was considered to be the only variable under the control of the printer. The ink, print cartridge, media, and print modes had to be developed to deliver the appropriate reflectance spectra and therefore colors to meet the market needs.

Color measurement can be done with two types of instruments: either a colorimeter or a color spectrophotometer. A colorimeter is designed to measure the XYZ tristimulus values directly, relative to a specified illuminant and observer. A spectrophotometer measures the reflectance spectrum such that the XYZ tristimulus values for any combination of source and observer can be subsequently calculated. A colorimeter is useful for relative measurements while a spectrophotometer is designed more for absolute measurements. The flexibility of the spectrophotometer comes at an additional cost, as might be expected.

Further Manipulations of CIELAB

CIELAB is a rectangular coordinate system in which L^* is the lightness color coordinate, a^* is the red-green coordinate, and b^* is the yellow-blue coordinate.

It is often useful to monitor the color of a sample using hue and chroma metrics because these yield information similar to the Munsell system. In the CIELAB system, hue (h) can be defined as the arctangent of the a^* and b^* coordinates, and chroma (C^*) is the radial distance from the L^* axis as represented in Fig. 1:

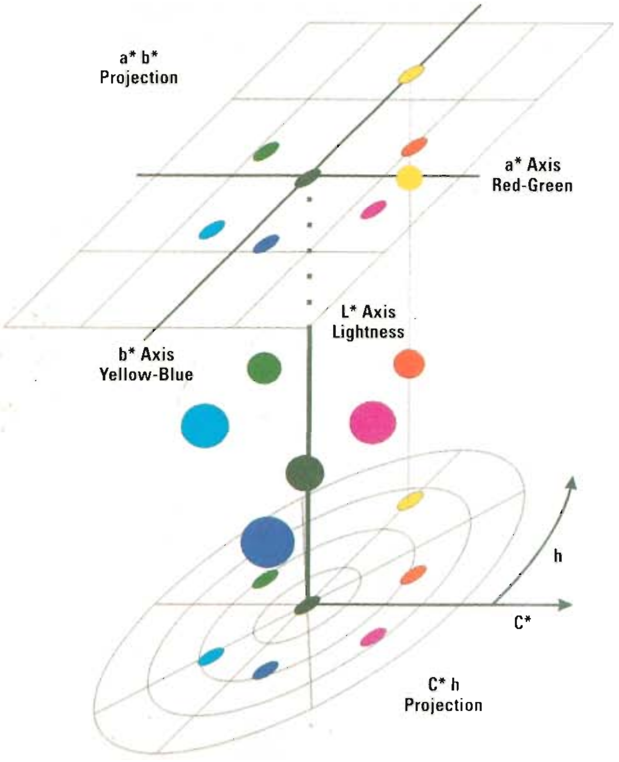

Fig. 1. 3D representation of the CIELAB space showing projections onto the a*b* and C*h planes.

$$h = \arctan(a^*/b^*)$$

$$C^* = \sqrt{a^{*2} + b^{*2}}.$$

Hue and chroma derived from the CIELAB space are not the same as the Munsell hue and chroma.

Another quantity derivable from the CIELAB values is color "saturation," which gives a sense of the depth of color:

$$S^* = C^*/L^*,$$

where S^* is saturation and C^* and L^* are defined above.

The difference between two colors can be easily described using the CIELAB system. Since each color is described by three coordinates, the color difference can be given by the vector length between the two colors, as shown in Fig. 2. A color match is obtained when the vector difference is zero, or the two colors have the same L^*, a^*, and b^* values. The vector difference between the two colors is called ΔE^* and is given by the following equation:

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}},$$

where ΔL^* is the difference in L^* values, Δa^* is the difference in a^* values, and Δb^* is the difference in b^* values between the two color samples.

Other color difference metrics can be defined, such as ΔC^*, the difference in chroma. Care needs to be taken with ΔE^* because the critical ΔE^* for a color change to be noticeable depends on the color of the sample. Yellows are forgiving while reds are not.

The selection of the appropriate color difference metric depends on the task for which it is being used. ΔE^* is a scalar quantity. It gives the size of the color difference but not the direction. Breaking ΔE^* into its components often yields more useful data because the direction and main component of the color difference can be obtained.

Uses of Color Measurement

Process Control. During the development of the color print cartridge it was important to maintain constant colors. Variations in the color output over time can be caused by many variables. Measuring the color printed with a print cartridge gave some measure of process control. Other methods of process control could have been implemented but colorimetric data is particularly useful because the process limits are related to human perception.

Dye and Ink Selection. Both the dye and the ink vehicle affect the colors generated with the color print cartridge. Given target colors, inks can be formulated to match the targets. Colorimetric data is particularly useful here, especially CIE hue. The hue values of the secondaries are very important and depend strongly on the dye selection. For a given set of dyes, saturation was also found to be a useful metric.

Grey Balancing. Because the HP DeskJet 500C is a one-print cartridge color printer, black must be printed with a mixture of the CYM primaries. The best black was not obtained with a tertiary black but by using a different ratio of C:Y:M. Color measurement was used to optimize the ratio of cyan, yellow, and magenta to print when black was requested. This had two benefits. The first is that the quality of the black print is improved because the best possible black is printed. The second is that less ink is needed to print this black, so the bleed performance of the printer is improved.

WYSIWYG Printing. Just as measurement spaces can be mapped onto visually based spaces, process spaces can also be mapped onto any color space. This makes it possible to print device independent colors and duplicate the desired colors. For example, CRT monitor colors are described by their own process space, RGB. There is a one-to-one mapping, very dependent on the particular monitor, between RGB and CIELAB. There is also a one-to-one mapping between CIELAB and the printer CYM space. By knowing both maps the colors shown on the monitor can be accurately duplicated on the printer, yielding WYSIWYG printing (What You See Is What You Get). The success of this process depends on the characterization of the mapping from the printer CYM space to the CIELAB space. This involves extensive color measurement and characterization of the printing system using a spectrophotometer. Problems do occur with WYSIWYG printing when either the printer or the monitor cannot print or display the requested colors. Sophisticated image manipulation has to occur so that a successful mapping can be accomplished.

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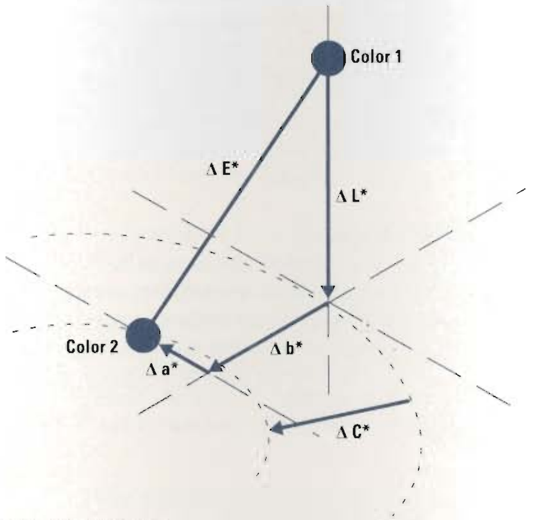

Fig. 2. Color difference metrics.

To guarantee print cartridge performance, the condition of the ink over the life of the print cartridge was determined. Even in an enclosed system such as the HP DeskJet print cartridge, there is vapor loss over time through the plastic walls. This vapor loss alters the ink vehicle composition and can ultimately affect the crusting performance. Once the rate of this loss was determined, inks were made up having vehicle compositions that a print cartridge would have at the end of its rated life. Dyes at various concentrations were placed in these vehicles and the crusting was tested. The maximum dye concentration that could pass the crusting test was established as the temporary maximum for that particular dye.

Next, a set of inks was made having a range of dye concentrations, from low up to the previously established temporary maximum. Print samples were made with these inks and the L*a*b* coordinates of the samples were measured (see "Color Science in Three-Color Inkjet Print Cartridge Development," page 71). If a dye showed a rebound point (the dye concentration at which color performance decreases because of overloading), the rebound point was set as the new temporary maximum. These temporary maximum dye concentrations were then corrected for the effects of vapor loss so that the ink performance would be maintained throughout the projected print cartridge life.

The next step in the process of color balancing was to determine what colors were most important in the color DeskJet printers. The relative order of desirability of various reds, blues, and greens for secondary colors was established by market studies. The ratios of the different dyes needed to produce the optimum red, blue, and green secondaries were then determined by trial and error.

For example, the concentration ratio of magenta to yellow that produces an optimal red might be 1.8:0.7. The optimal ratios for the blue and green secondaries of the dye set would be different. In most cases the ratios didn't match exactly. For instance, you could use the magenta-to-yellow ratio to get a good red. Then you could use that magenta concentration with the optimal ratio of magenta to cyan to get a good blue. However, the resulting cyan and yellow concentrations would then not be optimal for green. Consequently, optimizing the overall color palette required that some trade-offs be made.

In making the trade-offs and arriving at the final dye concentrations for use in the ink, an anchor dye and concentration were chosen. This anchor dye was chosen by evaluating the effect of dye concentration on chroma. The dye whose chroma level was most sensitive to dye concentration was chosen as the anchor dye. The concentration of this dye was determined by using the temporary maximum ratios obtained earlier in conjunction with the optimal ratios needed to achieve good secondaries.

For instance, say that yellow is chosen as the anchor color and that the maximum concentrations for magenta, cyan, and yellow are 5%, 4%, and 4%, respectively. In addition, say that the optimum ratio of magenta to yellow for achieving a good red is 2.5:1 and the optimum ratio of yellow to cyan for achieving a good green is 1.5:1. The new concentration for yellow is then calculated by dividing the maximum concentrations of the added colors, cyan for instance, by the optimal mix ratios. In this example, this yields a yellow concentration of 2.0% in the case of the red secondary and a concentration of 2.7% in the case of the green secondary. The smallest of the two secondary concentrations is then chosen as the maximum concentration of the anchor color, which in this case is 2% yellow for the red secondary.

Once optimal concentrations were found for the other two primaries in relation to the anchor dye concentration, print samples were made using inks with these dye concentrations. Based upon a visual evaluation of the print samples, the concentrations of the two dependent primaries were varied to make various trade-offs in the secondary color space.

For instance, it may be acceptable to alter the hue of the red slightly to achieve a markedly better blue. This final stage of color balancing involves repeated trials and fine tuning of the two dependent primaries within the bounds established by the temporary maximum concentrations. The process of printing samples, evaluating the color space, and then making concentration adjustments was repeated to arrive at the most acceptable color space.

Matching the Ink and Printhead

Thermal inkjet ink, printhead, and printer design are all excellent examples of highly interactive technology development. Development progress cannot be made on an inkjet ink formulation without at the same time having an appropriate printhead and printer in which to test the formulation. Likewise, printhead architecture and printer development efforts are very closely coupled to the performance characteristics of the ink formulation. Progress cannot be made in any one of these three arenas without the aid and support of the other two. This very interactive development environment presents a variety of technological and organizational challenges. In this environment, a carefully constructed ink screening strategy was required for timely printer system development.

The ink screening strategy that was used for the color HP DeskJet 500C/DeskWriter C print system development was based on rapid iterations of ink formulation, print cartridge architecture, and printer test beds. Empirical performance testing was conducted on dozens of ink formulations over a period of a few short months to determine the final ink composition. A progressively wider variety of tests were run on each ink formulation and printhead architecture combination. Once a given combination had passed quick, easy-to-complete initial testing, it was progressively subjected to tests requiring greater time and resource investments. The intended outcome of this effort was a printing system that provided outstanding plain paper color printing performance over a wide range of media and printing environments.

For a given printer resolution, the interaction of ink, print modes, and print media determines the final print quality. As discussed earlier, this interaction is largely controlled by the nature of the ink vehicle. For a given droplet volume, different ink vehicles will produce differing dot sizes on the various types of media. Ideally, one would like absolute control of dot size and placement. Given an attractive ink formulation, variations in the printhead architecture are used to control dot size and placement (see "Thermal Inkjet Review...," page 67).

To produce optimal print quality, the ink and the delivered drop volume need to be carefully matched. If the drop volume is too low, paper coverage will be incomplete. This results in desaturation of colors and irregular area fill. When the drop volume is too high, resolution and edge acuity suffer, and adjacent colors have a greater tendency to bleed into one another. Local printhead architecture largely determines the delivered drop volume. The surface area of the thin-film drive resistor and the exit diameter of the nozzle bore are the most significant factors in determining ejected drop volume. Ink viscosity, surface tension, and the size and shape of the photosensitive barrier film that surrounds the thin-film resistor largely determine the frequency response of the thermal inkjet device.[2] These are the main variables used by the printhead designer to optimize print quality and speed. These variables were tailored for each of the ink formulations tested.

Printhead Performance Tests

Candidate ink formulations were subjected to a wide range of performance tests. This regime consisted of both printing and print cartridge reliability tests. The central theme behind all of this effort was to test the print system's ability to deliver outstanding plain paper color print quality consistently over the life of the printhead.

The printing tests were conducted over a large sample of different media types. An international selection of "plain" papers was included in the sampling. In addition, printing performance was measured on HP LX JetSeries transparency film and HP CX JetSeries special paper. These special media products have been developed by HP to provide maximum thermal inkjet print quality. In addition to printing on a large number of different media, testing was conducted using different settings of the printer driver intensity control (see article, page 93). Environmental conditions for printing were systematically varied to cover the printer operating environment (5°C to 40°C, 10% to 80% relative humidity).

Several specific print quality attributes were examined during the course of the performance tests. These attributes include color bleed, color saturation, composite black text quality, and "waitbanding" performance (defined later).

As discussed earlier, color bleed is defined as the undesirable intermixing of two different colors when printed immediately adjacent to each another (Fig. 1). This intermixing results in an irregular deviation from the intended color interface profile. It is most visible when the two colors are of high relative contrast. Yellow and red or yellow and black are the color pairs most often tested for color bleed. Color bleed was quantified by visual comparisons against a set of standards. These standards were prepared such that varying degrees of bleed were produced. A bleed index number was then assigned to each of the standards. In addition to being a strong function of ink formulation and delivered drop volume, color bleed is also closely coupled to the dot density, media, and printing environment. It is aggravated by high temperature and high humidity. A significant portion of the color bleed testing was completed at temperatures of 35°C to 40°C at 80% relative humidity.

Color saturation was quantified using either spectrophotometers or colorimeters (see "Color Science in Three-Color Inkjet Print Cartridge Development," page 71). It is defined as:

$$S^* = C^*/L^* = \sqrt{a^{*2} + b^{*2}}/L^*$$

where: C^* = measured color chroma
a^* = red-green color coordinate
b^* = yellow-blue color coordinate
L^* = lightness color coordinate.

The major factors affecting color saturation include colorant concentration, vehicle formulation, drop volume, print mode, media, and printing environment. A cold, dry printing environment was found to reduce color saturation. Testing for color saturation was completed at 5°C to 10°C and 10% to 15% relative humidity.

The creation of high-quality black text characters and area fills using composite black is a particularly demanding task. As was the case for color bleed, internally generated comparative standards were used to quantify composite black performance. Ink vehicle formulation, color balance, and printing media are the factors most strongly influencing composite black text and area fill quality.

Waitbanding is a rather interesting printing artifact associated with the nonsimultaneous raster printing of colors. The nozzle arrangement in the color printhead is such that the different colors are printed serially onto the print media (Fig. 2). Cyan is the first ink to be delivered to the page, followed by magenta, then yellow. Nozzles for the three colors are spatially separated on the printhead by four dot rows (4/300 inch) in the paper advance direction. This results in a time separation of successive color ink delivery on the order

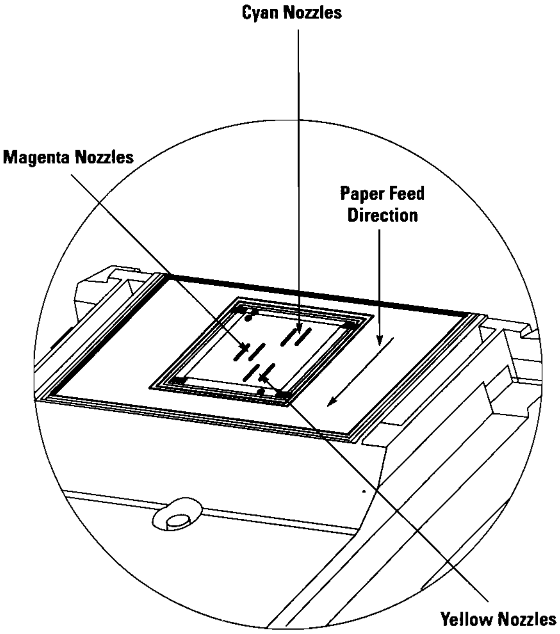

Fig. 2. The nozzle arrangement in the color printhead is designed to deliver the three colors serially to the media, cyan being the first. Sixteen nozzles are provided for each of the three colors.

of 1 to 2 seconds, depending on print mode and scan width. During the time interval between delivery of one color and delivery of the next, there is a significant amount of media penetration and evaporation of the ink vehicle. When mixed, or secondary colors (red, green, blue, and composite black) are formed, two or more of the primary colors are delivered to a given local area of the print media.

Waitbanding can occur if the time interval between successive raster scans during printing is significantly varied when creating secondary colors. When this time interval is varied, differing amounts of ink penetration and evaporation take place before the next primary color is printed onto the first primary color. The result can be the creation of a horizontal band of varied lightness and chroma. This variation in color appearance was quantified using the following color difference relationship:

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}},$$

where ΔL^*, Δa^*, and Δb^* are the differences in the color coordinates in the region of the waitband relative to an adjacent region outside the waitband.

The control of the time interval between scans involves a rather complex interplay between the user's computer hardware, the application software, the operating system, the communication network to the printer (if used), and the printer processor and firmware. Several steps have been taken in the development of the color HP DeskJet 500C/DeskWriter C system to minimize the variability in the time interval between successive scans and its impact on waitbanding. Ink formulation also can play a major role in minimizing the magnitude of the waitband color difference. It is for this reason that waitbanding testing was included as one of the screening parameters in the ink formulation selection regime.

Several print cartridge performance attributes not directly associated with a print sample were measured as well. In addition to safety and regulatory considerations (see page 76), the selection of ink components is also often limited by compatibility with the other materials in the printhead and printer system. These system-level limitations are typically determined using elevated temperature materials compatibility and printhead tests. In their simplest form, these tests consist of immersing a given printhead or printer component in the ink or ink constituent of interest. The immersed component is then subjected to elevated temperatures for a period of several weeks. Degradation of the component and changes in the ink or ink constituent are then measured at the end of this period. Arrhenius modeling[3] of degradation reaction rates is often used to assess the impact on print system longevity and reliability.

Reducing the tendency for the very small printhead nozzles to clog or crust over presents an ongoing challenge for the ink chemist and product designers.[4] Ink formulation testing for the time to the first misdirected droplet was conducted throughout the ink development effort. The major printhead design factors affecting crusting behavior include colorant species and concentration, vehicle solvents, and the environment in which the printhead is being operated. The printer designers can contribute to the prevention of clogging by providing special print cartridge servicing functions. These functions include tight capping of the print cartridge's orifice plate when not in use, plus periodic wiping and firing of the nozzles before and during printing.

An additional area of ink formulation screening is kogation testing. As discussed earlier, kogation is defined as the plaque-like buildup found on the thin-film resistor surfaces of thermal inkjet devices after many firings of the printhead.[4,5] Kogation testing consists of monitoring the drop volume or color saturation a given printhead produces over the full lifetime of the head. Careful selection of ink constituents and control over the thin-film resistor drive energy are needed to reduce or eliminate kogation problems.

Ink Quality Control

The inks for the HP DeskJet 500C and DeskWriter C printers were carefully formulated to provide outstanding performance on a wide variety of plain papers. Careful control of ink component concentrations and purities during ink production is critical to ensure that customers receive consistently good performance from their print cartridges.

The consequences of ink impurities or incorrect ink component concentrations can be quite severe. For instance, incorrect dye loads and impurities in the dyes can cause significant shifts in the hues that are produced by the printer. Incorrect pH values can cause chemical instabilities in the ink as well as undesirable interactions with some of the print cartridge materials. Incorrect ink viscosity can drastically alter the firing characteristics of the print cartridge, resulting in poorly formed droplets and poor print quality. Improper concentrations of certain vehicle components can lead to a loss of bleed control between different colors. Impurities in the dyes or other vehicle components can cause nozzle plugging and reduce bleed control and print quality.

The physical ink parameters that are monitored include: static surface tension, viscosity, pH, solution absorbance, and conductivity. A Hewlett-Packard 5890A gas chromatograph (GC) with an HP 9000 Series 300 workstation is used to determine the concentrations of some of the components in the ink. In addition, the GC is used to verify the purity of one of the ink constituents before it is added to the ink. Dyes are purified using a variety of procedures including reverse osmosis. Selected ion levels are monitored using atomic absorption spectrometry.

Not all of the components in the ink are determined by a specific analytical method. Certain practical compromises were necessary. The concentration of some components is very difficult to determine in the ink matrix or requires very specialized and expensive analytical equipment that is not cost-effective in a production environment. For these components, indirect methods are used to verify proper concentrations, along with the very careful use of process control procedures such as weight logs.

Delivery to the customer of consistent, high-quality output relies on many factors, one of which is a consistent ink composition. By carefully controlling ink component concentrations and purities, delivery of this consistent performance to the customer is ensured.

Making HP Print Cartridges Safe for Consumers Around the World

The ability to provide assurance that our products do not cause harm to consumers and the environment is central to Hewlett-Packard's thermal inkjet product stewardship. Ink safety evaluation is the most important part of the overall safety and regulatory process.

Thermal inkjet print cartridges contain liquid inks designed to deliver laser-printer-like print quality. These liquid inks contain dyes, solvents, and special additives, which are essential to the operation of the print cartridges. Chemists spend considerable time developing these inks and often synthesize new chemicals to improve print quality.

To ensure the safety and marketability of our print cartridges worldwide, all new ink and print cartridge ingredients are screened for potential safety (toxicology) and regulatory concerns during the research and development phase.

To begin with, all ingredients are screened to eliminate any ingredients that may elicit harmful toxic responses in humans and the environment. The scientific literature is searched to determine what is known about the ingredients. Structural activity relationships are used to estimate the toxicity of newly synthesized chemicals. In addition, a tier approach is used to determine the scientific tests to be conducted. The tier system consists of both Hewlett-Packard's safety standards and government regulatory requirements.

Regulatory concerns for newly synthesized chemicals used in ink and print cartridge development are more complex. Since we sell our print cartridges worldwide, we must obey all laws governing chemicals contained within an article—in this case the print cartridge. These laws differ by country and we must understand and develop inks accordingly. For example, in the United States our print cartridges are regulated by the Environmental Protection Agency (EPA) and the Consumer Product Safety Commission (CPSC).

To sell print cartridges worldwide, we must obey many rules and regulations. For example, in the U.S.A.,we must file a Premanufacture Notification (PMN) with the EPA before we sell a print cartridge containing a new chemical not listed on the United States master inventory. The cost for filing a PMN is about $2,500 per chemical and there is a 90-to-180-day waiting period for approval. There are substantial penalties for noncompliance.

In Europe our print cartridge inks are regulated by the European Economic Community. The EEC requires a series of scientific tests before we can market a print cartridge containing a new ink. These tests can cost from $50,000 to $150,000 per compound and take up to one year to conduct. In addition, the Europeans have a 45-day waiting period before allowing the sale of any new ingredients.

Japan's laws (regulated by the Japanese Ministry) are slightly more favorable for our print cartridges because they only require the registration of certain chemicals. Since none of our inkjet chemicals are listed on Japan's list of "hazardous chemicals" and our print cartridges fall under an article exemption law, we do not have to register our newly synthesized ingredients. However, the ingredients must not impose any health risk to humans and the environment.

Obviously, there are many more countries, laws, and regulations we must obey to sell our print cartridges worldwide. Our print cartridge and ink ingredients must be safe and free of any legal restraints. By addressing safety and regulatory issues during the research and development stage, Hewlett-Packard intends to continue to meet the needs of its many markets worldwide.

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Automated Assembly of the HP DeskJet 500C/DeskWriter C Color Print Cartridge

Roughly 60% of the assembly technology had to be developed especially for the color print cartridge. Plastic welding, adhesive dispensing, TAB circuit staking, and ink fill were among the challenges.

by Lee S. Mason and Mark C. Huth

One of the key considerations in the development of the color print cartridge for the HP DeskJet 500C and DeskWriter C printers was time to market. Because of this, every effort was made to leverage the design and assembly technology of the existing black print cartridge where possible, and to improve on the design where the opportunity presented itself.

Fig. 1 shows an exploded view of the color print cartridge. Fig. 2 shows the assembly line for this cartridge. Many of the stations were leveraged to some degree from the black print cartridge assembly line. The chart below lists the stations that were heavily leveraged (less than 20% of the station redesigned), moderately leveraged (20 to 70% of the station redesigned), and not leveraged (essentially a new design).

Heavily Leveraged	Moderately Leveraged	New Design
Bar-Code Label	0-1 Transfer	Nose Load
Head Attach	Date Code	Body Load
Head Cure	Print Test	Nose Weld
TAB Prep	Offload and Tape	Filter Stake
TAB Attach		Filter Stake Inspect
TAB Bond		Fail Offload
TAB Wrap		Adhesive Dispense
UV Cure		Adhesive Inspect
E-Test		Cheek Stake
1-2 Transfer		Side Heatstake
Pen Seat		Encapsulant Dispense
Clean and Dry		Foam Feed
Print Test Transfer		Foam Stuff
		Lid Load
		Lid Weld
		Ink Fill
		Cap Load
		Cap Weld

Areas of Improvement

The manufacturing development team identified six areas where there was significant opportunity to improve a process from the way it was performed for the black print cartridge assembly. These areas are:

- Cartridge Body Preassembly. A new subsection was added to the assembly line for preassembly of the two-part cartridge body and the filters.
- Bulk Part Feeding. Plastic parts, filters, and foam blocks are automatically fed into the assembly tooling from bulk part hoppers or bowls. These parts are delivered to the production line in bags and loaded into the hoppers as needed.
- Adhesive Dispense. Positioning and bead width control required substantial improvement for the color print cartridge.
- TAB Circuit Staking. To simplify the process for attaching the flexible TAB (tape automated bonding) circuit to the cartridge body, a direct staking process is used, eliminating the need for adhesive between the two parts.
- Ink Fill. The ink fill process was redesigned to allow more control of the process parameters.
- Throughput and Utilization. To make the assembly line more efficient, the fastest conveyor speed available is used, and the control of pallets through each assembly tool is handled by the process controller resident in the tool itself rather than a central line controller. To improve line utilization, space for part buffering between assembly processes was designed in, allowing parts to accumulate during short periods of tool downtime.

Production Line Layout

The basis for the color print cartridge production line is a "power and free" style conveyor system. In this system, two narrow, parallel conveyor belts run continuously. Square pallets rest freely on the belts, which move the pallets between assembly tools. These pallets contain fixturing that holds the print cartridge parts during assembly. All assembly and inspection operations are completely automated with the exception of prebond inspection. Operator responsibilities include material loading, finished product unloading, and tool and process monitoring.

The color print cartridge production line has three subsections referred to as Assembly 0, Assembly 1, and Assembly 2 (see Fig. 2). Each section uses its own unique pallet to fixture the print cartridge parts slightly differently, as required for that section's sequence of assembly.

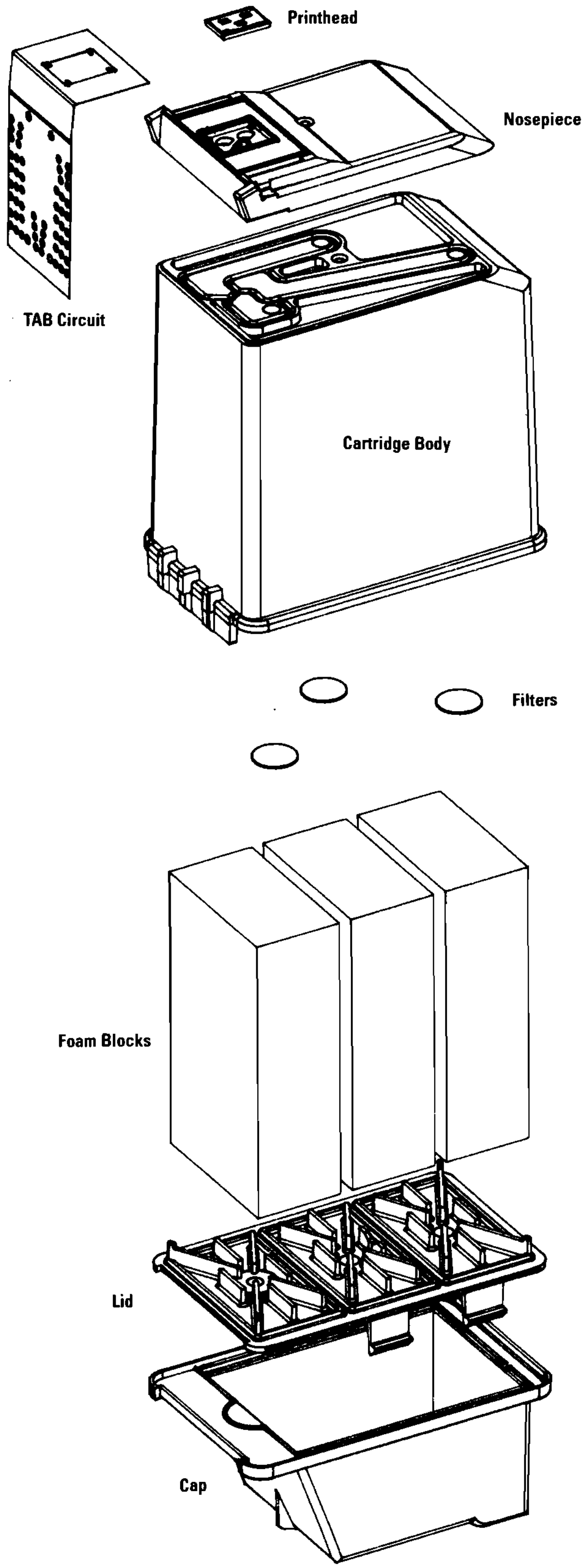


Fig. 1. Exploded view of the color print cartridge.

Assembly 0

This section of the line has the tools necessary for print cartridge body preassembly. It consists of two parallel and adjacent conveyor sections approximately 35 feet long. One conveyor moves Assembly 0 pallets between tools and the adjacent conveyor carries pallets with completed plastic body preassemblies back to the start of the next subsection of the assembly line.

The processes that occur during plastic body preassembly are nose load, body load, nose weld, filter stake, filter stake inspect, and fail offload.

At the nose load station, a plastic nosepiece is loaded into an empty Assembly 0 pallet. Vibratory bowl and inline feeders move the parts to a pick position, where a cam-actuated pick-and-place device grasps a nosepiece and places it into the pallet. A bulk hopper and elevator system is used to regulate the part level in the vibratory bowl.

The body load station loads the plastic body part into the Assembly 0 pallet on top of the nosepiece. It is virtually identical to the nosepiece load station except for the size and shape of the part being fed.

The nose weld station ultrasonically joins the plastic body and nosepiece.

At the filter stake station, a stainless steel mesh filter is heatstaked to the plastic body at the inlet to each of the three ink channels. Three parallel filter feeding and staking processes are used to accomplish this. In each process, the filter is first fed using a vibratory bowl to a pick position where it is picked using vacuum and presented to a heatstaking head by a pneumatically actuated pick-and-place device. The heatstake head then moves down into the plastic body and thermally joins the filter to the inlet of the ink channel.

After the three filters are staked into the plastic body, machine vision is used to inspect the quality of the process automatically. The filters are inspected for presence and location, and the completeness of the weld is determined. For a more detailed description see the article "Machine Vision in Color Print Cartridge Production," page 87.

The last process in the Assembly 0 subsection is the fail offload station. Here any plastic body preassemblies that have failed filter inspection are ejected from the Assembly 0 pallet into a scrap container.

Assembly 1

Assembly 1 consists of the operations that are performed with the nozzle (or printhead) side of the pen facing up. This subsection is configured in a large rectangle about 50 feet long and about 10 feet wide.

The stations on the Assembly 1 portion of the line are 0-1 transfer, bar-code label, adhesive dispense, adhesive inspect, head attach, head cure, date code, TAB prep, TAB attach, cheek stake, TAB bond, TAB wrap, side heatstake, encapsulant dispense, UV cure, and E-test.

The 0-1 transfer station uses a pneumatically actuated robot to remove the pen bodies from the Assembly 0 pallet, rotate them 180 degrees and place them onto the Assembly 1 pallet. The Assembly 1 pallet uses a set of two metal locating mandrels which fit inside the cavity of the pen body assembly to locate two pen bodies precisely on each pallet. Assembly 1 is the only subsection of the line that has two pens on a single pallet. This lowers the cycle time. The cartridge orientation necessary for the Assembly 0 and Assembly 2 operations prevented having more than one cartridge on a pallet.

The labeling machine applies a bar-code label to each pen body assembly. The bar-code label is used in downstream processes.

The adhesive dispense station uses x, y, and z servo-driven positioning tables and a metering pump to dispense the adhesive that secures the printhead to the plastic pen body assembly. Adhesive location and thickness are critical to proper adhesion of the printhead with no leaks between chambers. (Interchamber leaks cause contamination of the ink supply and will give unexpected colors.) For a more detailed description of the adhesive dispense operation, see the article on page 84.

The adhesive inspect station uses a machine vision system to verify that the adhesive pattern is complete and free of voids. For a more detailed description of this operation, see the article entitled "Machine Vision in Color Print Cartridge Production," page 87.

The head attach machine consists of several high-precision servo-driven positioning tables, a machine vision system, and a system controller. The machine removes the printhead die from a film frame, and using machine vision, aligns the pen body assembly with the die. The die is then placed into the adhesive previously dispensed by the adhesive dispense station. This machine must locate the printhead with respect to the pen body assembly within extremely tight tolerances to ensure proper operation of the print cartridge. For a more detailed explanation of this piece of equipment, see reference 1.

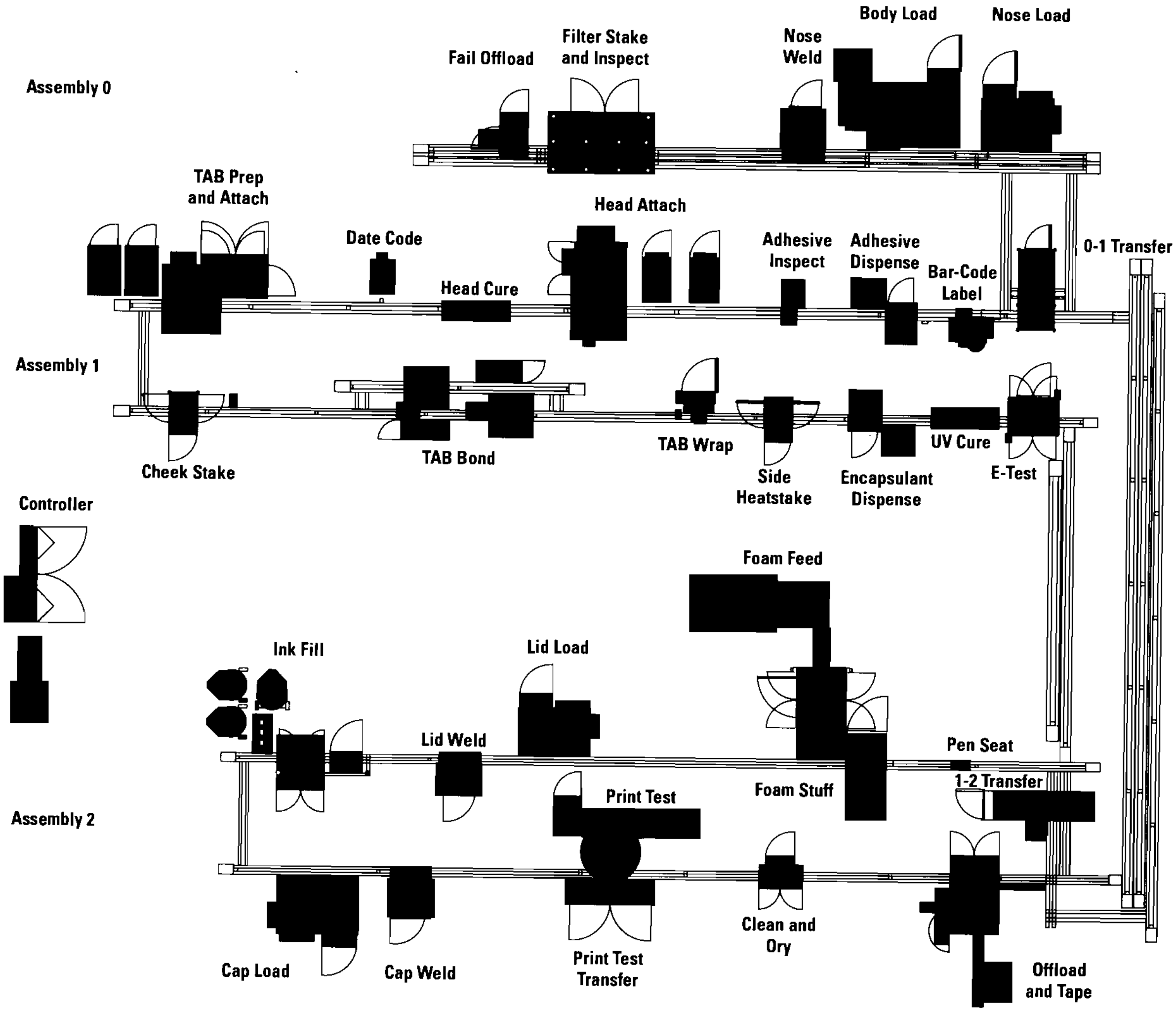


Fig. 2. Color print cartridge final assembly line.

The head cure station thermally cures the adhesive that attaches the printhead to the plastic pen body assembly. The head cure station consists of several identical stations in series, and the adhesive is partially cured at each station. Acceleration and deceleration of the pallets must be carefully controlled in the head cure stations to prevent printhead shift while the adhesive is in its uncured state.

The date code station uses an inkjet printer to imprint a date code onto the plastic pen body assembly. The date code is used within the Inkjet Components Division to track date of manufacture, thin-film printhead lots, yields, and other information.

The TAB prep machine unrolls the raw TAB stock from a reel, uses machine vision to inspect the part, and punches and presents good parts to the TAB alignment machine.

The TAB attach machine uses machine vision and servo-driven positioning tables to align the pen body assembly precisely with the TAB circuit. The TAB circuit provides the electrical interconnect between the pen's printhead and the printer. Once the alignment has been performed, the TAB circuit is tacked into place using a heated probe.

The cheek stake tool uses a heated platen to melt the plastic nose beneath the TAB circuit to attach the cheeks of the TAB circuit permanently to the pen body assembly. The platen is compliant, which is necessary to ensure that the entire surface of the TAB circuit adheres to the pen body assembly.

The TAB bond machines ultrasonically weld the "beams" of the TAB circuit to the interconnect. The station uses machine vision to align the ultrasonic probe with the TAB circuit.

The TAB wrap tool engages the tooling holes in the TAB circuit, folds the TAB circuit over 90 degrees, and holds it in position while it is tacked into place using a heated probe.

The side heatstake tool is similar to the cheek stake tool described previously. It uses a heated platen to melt the plastic pen body beneath the TAB circuit to attach the side of the TAB circuit permanently to the pen body assembly. The platen is compliant, which is necessary to ensure that the entire surface of the TAB circuit adheres to the pen body assembly.

The encapsulant dispense station is very similar to the adhesive dispense station. It uses x, y, and z servo-driven positioning tables and a metering pump to dispense the adhesive that protects the exposed beams of the TAB circuit. Reflective laser sensors are used to locate each pen body assembly precisely before dispensing the encapsulant.

The UV cure station cures the encapsulant adhesive with ultraviolet light. After cure, the bonds are stressed to break any TAB bonds that might otherwise fail in the field.

The E-test is the final station in the Assembly 1 subsection. Using a spring probe block, it electrically verifies all of the interconnections between the printhead and the TAB circuit.

Assembly 2

The last subsection of the assembly line consists of assembly and test operations performed with the printhead facing down and the ink containment cavities facing up. Assembly 2 consists of a conveyor loop approximately 45 feet long and 10 feet wide. One cartridge is held on each pallet. The operations that occur in Assembly 2 are 1-2 transfer, pen seat, foam feed, foam stuff, lid load, lid weld, ink fill, cap load, cap weld, print test transfer, print test, clean and dry, and offload and tape.

The 1-2 transfer station uses a pneumatically actuated robot to remove print cartridge assemblies from the Assembly 1 pallet, rotate them 180 degrees and place them into the Assembly 2 pallet.

The pen seat station uses a pneumatic cylinder to ensure that the print cartridges are completely seated within the pallet. This prevents damage to the downstream tools.

The foam feed system consists of a bulk hopper, a cleated belt elevator, and vibratory feeders, which deliver foam blocks to the three inlet positions of the foam stuff machine. The foam blocks are dropped into the compressor section of the tool, which compresses the foam in two axes. A ram then pushes the foam blocks up into three sheet-metal tubes with rectangular cross sections. The tube set is then moved down into the pen body and a ram drives the foam out of the tubes and into the pen body. The motions of the tubes and the ram during the stuffing sequence are precisely controlled by motor-driven cams.

At the lid load station, the plastic lid is loaded onto the top of the cartridge to cover the foam blocks. Vibratory bowl and inline feeders move the parts to a pick position where a cam-actuated pick-and-place device grasps the lid and places it onto the cartridge. A bulk hopper and elevator system is used to regulate the part level in the vibratory bowl.

The lid weld station ultrasonically joins the plastic lid and body.

The ink fill process is initiated by forming a chamber around the print cartridge and evacuating the chamber to a high vacuum. Ink is pumped into the cartridge using hollow needles, which pass through the three holes in the plastic lid.

The cap load station places the plastic cap onto the top of the print cartridge assembly. The purpose of the cap is to provide a handling surface for the user and to minimize water vapor loss from the cartridge over its life. This station is similar to the lid load station and the other plastic part loading stations.

The cap weld station ultrasonically joins the plastic cap and body. It is the last assembly process on the line.

The print test system is used to evaluate the print quality of the cartridge. Each cartridge is transferred to a four-position rotary table to allow multiple operations to occur in parallel. At one position on the rotary table, electrical contact is made with the print cartridge and a test pattern is fired while a strip of paper is passed beneath the cartridge. The test pattern is then moved beneath cameras and a vision system is used to determine if all nozzles are firing correctly. For a more detailed description of print quality testing see the article on page 87.

The cartridge clean and dry station uses a water loop, which contacts the printhead surface and cleans off the ink residue left behind during print quality testing. After cleaning with water, the printhead is dried with heated air.

The last operations on the production line occur at the offload and tape tool. Here the cartridges are first sorted based on the results of the print quality testing. Cartridges that have failed the print test are offloaded from the pallet onto a conveyor for removal by an operator. Cartridges that have passed print testing are offloaded from the pallet into a tool that tapes the printhead area to contain the ink during shipping and storage. These cartridges are then offloaded onto a separate output conveyor for removal by an operator.

Continuous Development

Many challenges were encountered during the startup phase of the high-volume color print cartridge production line. Initial yields were very low on the high-volume line, roughly 50% of what was seen on the prototype line. There were two main reasons for this discrepancy in yields. First, prototype yields were misleading because relatively few pens were built on the prototype line. Second, in an effort to get as many good test pens as possible, pens were "nursed" through the prototype manufacturing process. Unfortunately, most of these special steps were not readily transferable to the high-volume production line.

The low yields at initial line startup triggered an intensive series of experiments to determine how yield could be improved. Based on the results of these experiments, several new processes were developed and new stations were designed and implemented on the assembly line.

Many of these new processes are proprietary. One that is not is the addition of pallet decelerators in numerous places around the line. The production line uses very small, lightweight pallets, and to keep cycle times to a minimum, the line uses the highest-speed Bosch conveyor. Light pallets and fast belts combine to transfer large shock loads to the parts and may shift the positions of any loose parts. The pallet decelerators reduce these shocks and allow us to benefit from lighter pallets and faster belts without compromising pen quality.

Impact of Leverage

As mentioned earlier, some portions of the color print cartridge design were heavily leveraged from the previously introduced black print cartridge. Our team learned that when it comes to leverage, more is better. The portions of the assembly technology that were not leveraged from the black cartridge (roughly 60% were not) provided the most challenges and headaches.

For example, the development of a two-piece nose and body that can be ultrasonically welded together to form the three separate ink channels of the printhead ink path was extremely challenging (see "Color Inkjet Print Cartridge Ink Manifold Design," page 82). The plastic material was difficult to weld. So much energy was required to produce the weld that the weld horns would stress crack after a few hundred parts. Fabrication tolerances of the two molded plastic parts were very tight and critical to achieving leak-free welds.

The process tolerances for this product required a total redesign of the adhesive dispense equipment. The equipment was custom-designed in-house (as was most of the color print cartridge assembly equipment) because no commercial dispense systems could meet the critical locational tolerances. The color print cartridge also requires different types of adhesives because the color inks are not compatible with the adhesives used on the black print cartridge.

This print cartridge was the first to use heatstaking to adhere the TAB circuit to the plastic body. (The black print cartridge uses patches of die-cut hot melt adhesive to bond the TAB circuit to the body.) The compliant design of the cheek and side heatstakers allows the entire surface area of the TAB circuit to adhere to the body, even without the compliance provided by the soft hot melt patches.

Because of the three different-colored inks and three foam blocks, a special approach was necessary in the foam stuff process. The foam stuff machine was totally redesigned to accomplish the compression and simultaneous insertion of the three small foams.

The formulation of the colored inks presented numerous challenges to the ink fill process. During ink fill, the print cartridge is filled with ink and the ink front moves through the ink channels to the printhead. The print cartridge is first placed in a chamber and the air is evacuated. The vacuum level must be precisely controlled during the entire operation or one of several failure modes may be induced. The ink may froth as it is pulled past the print cartridge's filters. This produces a print cartridge that is prone to "drooling." (Drooling is ink dripping out of the printhead without the print cartridge's being fired.) The print cartridge may contain air bubbles and fail the print quality test. The ink must be removed from the surface of the printhead quickly as the ink front moves past the nozzles. If it is not, the inks will mix on the surface of the printhead and contaminate the ink supply. Dozens of enhancements were made after the ink fill station was online as we gained a better understanding of the process.

The last major deviation from the process for the black print cartridge involves the nozzle taping operation. The tape requirements for the color print cartridge are much more restrictive than for the black print cartridge. First, a tape leak in the color print cartridge will result in ink mixing, which is a functional failure. In the black print cartridge a tape leak is only a cosmetic concern. Second, the primitives (groups of ink nozzles) in the color print cartridge are very close together and close to the edge of the printhead. These factors make tape leaks much more probable with the color print cartridge. Proprietary process changes in the manufacture and application of the tape allowed us to solve these taping problems.

Color Inkjet Print Cartridge Ink Manifold Design

In a disposable printhead, the ink reservoir, the ink plumbing, and the ink firing device must reside within the print cartridge. One of the challenging aspects of the print cartridge design for the HP DeskJet 500C and DeskWriter C printers was the creation of the manifold required to deliver ink from the foam ink reservoir to the printhead. This article deals with the parts and processes used to create this manifold.

Ultrasonic welding is used to join the two parts that form the manifold. This process had been used on the previously released black inkjet pen to attach the plastic cap to the plastic body. Building on some of the prior welding experience, a joint was designed.

Joint Design

The joint is a double shear joint, mainly because the literature strongly suggested that shear joints are the best joint design for obtaining a hermetic seal. In designing an ultrasonic weld joint, three basic requirements must be met:

- Small initial contact area between the two parts. This concentrates the energy to allow the material to melt faster, reducing weld time.
- Uniform and intimate contact. The entire weld joint should be in uniform contact with the mating part. This allows uniform energy distribution to the entire weld joint.
- A means of alignment. If the joint does not provide a means for aligning the parts, some other means (e.g., pin and sockets) must be used.

Fig. 1 shows the weld joint cross section geometry. The small initial contact area is obtained by having the sharp corners of the male piece (nosepiece) interfere with the chamfer in the smaller opening of the female piece (print cartridge body).

Tight molding tolerances are required on both parts to maintain uniform and intimate contact. Fig. 1 also shows how the manifolds are formed by the weld joint. This weld line is not a simple straight line but a rather complicated irregular shape. Obtaining the tight design tolerances challenged the technology of multiple-cavity mold generation and plastic injection molding. All plastic parts were modeled as three-dimensional solids using the Hewlett-Packard ME 30 system. The 3D bodies were used to generate the tool paths for CNC-machining the electrodes used to make the molds.

Part alignment is obtained by the fit of the male piece into the chamfer on the female portion, which accurately locates the two parts with respect to each other.

Equipment

The welder consists of a power supply and an actuator. The power supply converts line voltage, 220V at 60 Hz, to 1,000V at 20 kHz, and also contains the controls for setting weld time or weld energy and trigger force. The 20-kHz electrical signal is converted to mechanical vibration by a piezoelectric transducer called the converter. The actuator holds the converter, booster, and horn. It also provides the controls for down speed and ram air pressure, and houses the encoder for determining horn location. The actuator is mounted on a rigid stand. While parts are being welded, they are held by a nest attached to the production line.

Weld Theory

Ultrasonic welding works by causing friction between two interfering plastic parts. This friction is present on both the microscopic and macroscopic levels. The heat generated by the friction melts the plastic at the weld joint. While the plastic is molten, further vibration causes polymer chains of the mating parts to intermingle. As the plastic cools, the two parts become one. When an ultrasonic weld is done correctly, the physical strength of the joint approaches that of the parent material. There are many benefits to using this method for joining plastics, not limited to the following list:

- It does not require the use of solvents or adhesives (no need for added ventilation).
- Part count is reduced (no need for gaskets, mechanical fasteners, etc.).
- It is easy to integrate into an automated assembly process (microprocessor control, fast cycle time).
- The highly localized heating results in little or no part deformation.

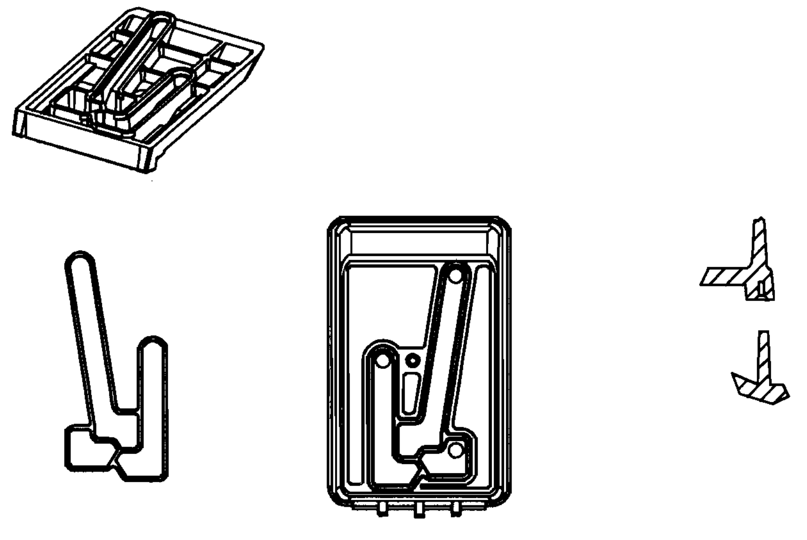
Process Variables

The mechanical energy delivered to the parts can best be described as a function of force, amplitude, frequency, and weld time. Force is dependent upon air pressure, ram area, down speed, and trigger force. Air pressure can be adjusted via a regulator. Ram area is a constant. Down speed is adjusted by regulating the flow on the backside of the ram. Trigger force is read from a transducer, and the triggering level can be varied and controlled by the power supply. The amplitude present at the horn/part interface is defined by the equation:

Amplitude = (Converter Output) × (Booster Gain) × (Horn Gain).

Converter output is constant at 0.0008 inch. Booster gain can be varied in discrete amounts. Horn gain is constant and depends upon the horn design. Frequency is a constant, in this case 20 kHz, although welders can be purchased with different frequencies. Weld time is a variable that can be adjusted and controlled by the power supply. Therefore, the way in which energy is delivered to the plastic parts can be varied by as many as five independent variables.

One of the more important parameters affecting weld quality is the amplitude of the mechanical energy. The "stack" used to deliver the weld energy to the plastic parts consists of the converter, the booster, and the horn. The horn is an acoustically



Nose Detail **Body Detail** **Section Detail**

Fig. 1. Weld joint cross-section geometry.

tuned part that transfers the vibration into the plastic parts. The booster is an acoustically tuned coupler used to connect the horn to the converter. The size and shape of a booster affect its gain. Standard booster gains range from 0.5 to 2.5. The amplitude can be varied by interchanging boosters with differing gains. As mentioned previously, the converter is a transducer that converts the electrical signal to a mechanical vibration.

Process Development

To define a process for welding these parts it was necessary to understand how each variable affected the quality of the weld. Moreover, a method for quantifying the quality of the weld joint was needed. The quality of the joint was measured by how well it met the part objectives, namely parallelism and leak tightness. The parallelism was measured with a drop indicator, a fairly trivial task. Deciding how to check for leaks, however, became a long affair with many unacceptable methods tried. At long last, it was decided that a sensitive pressure leak tester would be sufficient for leak testing. The quest became one of correlating the inputs (pressure, weld time, down speed, trigger force, and booster) with the outputs (leak rates in three chambers and datum parallelism). One of the largest advancements in process development came from using an experimental design and statistical analysis program to model the correlation. This program proved to be invaluable in choosing the parameters for the process.

The use of the program was an iterative process. A very broad-based experiment was first designed to determine which variables and interactions were significant. These results often yielded trends in variables that would further limit the possible operating conditions. These possible operating conditions were then used as center points for narrower experiments. This iteration continued until an acceptable operating condition was attained.

Pitfalls

This has not been an easy road. There have been some pitfalls associated with ultrasonic welding as well. These include horn manufacture and reliability, and tight plastic molding tolerances.

As described above, the horn is an acoustically tuned part used to transmit the vibratory energy into the plastic parts. The two metals commonly used for horn manufacturing are aluminum and titanium because of their good acoustical properties. During a horn's use, it undergoes longitudinal flexure and compression. The stresses involved depend upon the amplitude of the strain within a horn element. Horns are usually manufactured to handle half-wavelength and full-wavelength vibrations. Half-wavelength horns have one node, while full-wavelength horns have two nodes. During vibration, the material at or near a node undergoes the largest stresses. The larger the stresses, the shorter the horn life, as is the case with typical fatigue failures. Early designs of the horn were half-wavelength. Unfortunately, this placed a stress riser very near the nodal region of the horn. This stress riser proved to be the source of fatigue cracking in these horns. By changing the design to a full-wavelength horn, we moved the stress riser to a more benign location, farther away from a nodal region. The full-wavelength horn was chosen as the long-term solution for the manufacturing process.

Further problems were encountered because of plastic part variation. When the multiple-cavity molds were brought up, there were numerous permutations of nosepiece and body combinations. Of all the possible part combinations, only a small fraction worked with the existing process. Finding a process that would work for all part combinations was extremely challenging. There are three possible alternatives for finding a solution to this problem: make the parts closer to the same (decrease the tolerances for acceptability), find a very wide process window that will weld parts that are not quite identical, or some combination of the two. The third solution was chosen. Trade-offs in part tolerances and process margins were made. By changing certain part tolerances, a process window was established that could weld all part combinations. This challenge will remain whenever a new mold is brought on line, as long as this joint design is in use.

Acknowledgments

The author was not alone in the work on the manifold design. The success of this design and process has been fashioned by the hands of many engineers. Of note are Michael Allison, Marvin Wong, Bill Peters, and Patrick Boyd.

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Conclusion and Acknowledgments

This project has been very successful for the Inkjet Components Division in Corvallis. The high-volume color print cartridge assembly line has come up to speed faster than any previous production line of its type, including duplications of the black print cartridge assembly line. This success is in large part because of the dedicated efforts of numerous groups and individuals. The manufacturing engineering project manager was Bob Conder. The manufacturing engineers who designed the line included Joe Santich, Bill Peters, Gary Lutnesky, Doug Reed, Mike Monroe, Dennis So, Wayne Traina, and Ken Frazier. We would also like to acknowledge the many contributions of the build technicians, maintenance technicians, and production operators.

Reference

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Adhesive Material and Equipment Selection for the HP DeskJet 500C/DeskWriter C Color Print Cartridge

The adhesive joins the printhead to the cartridge body and maintains color ink separation at the interface. The encapsulant protects the electrical bonds. Special equipment was designed to dispense these materials with high precision in very small volumes.

by Douglas J. Reed and Terry M. Lambright

Structural adhesive is the material that creates the bond between the active portion of the print cartridge (the printhead) and the passive portion (the cartridge body). Adhesive requirements for the three-color HP DeskJet 500C/DeskWriter C print cartridge are few, but critical. Sufficient bond strength must be provided over all environmental conditions throughout the entire lifetime of the print cartridge (a maximum shelf life of eighteen months and a maximum in-printer service life of six months). This requirement is very similar to the corresponding requirement for the original monochrome ink cartridge introduced with the HP DeskJet printer. However, the three-chamber design of the color cartridge adds the important function of maintaining color ink separation at the interface between the printhead and the cartridge body.

The primary role of the encapsulant is to provide protection for the bonds that are created between the TAB (tape automated bonding) circuit leads and the bond pads on the printhead. The TAB circuit is the device that carries electrical signals from the printer to the resistors on the printhead. The encapsulant also coats and protects the portion of the TAB leads that spans the gap between the edge of the TAB circuit and the edge of the printhead.

Stress Tests

To decrease product development test time, various accelerated stress tests were used to verify the acceptability of the adhesive systems over the projected lifetime. These stress tests exposed the adhesives (and the entire print cartridge in some cases) to mechanical, thermal, and other environmental stresses that were meant to reveal weak points in the design and assembly of the print cartridge. Because the ink is in contact with the adhesives during these tests, chemical interactions with the ink components are also accelerated. The rigorous test regimen used in this project was helpful in understanding the root causes of various failure modes.

Cycle-Time Constraints

To obtain the desired manufacturing cycle time, it was necessary that the structural adhesive and the encapsulant reach full cure in a relatively short time. Material selection was therefore restricted to adhesives that could be rapidly cured by an appropriate energy source. Multiple stations were necessary to obtain the required throughput, but by selecting quick-cure adhesives, cost was minimized by reducing the total equipment needs.

Compatibility with Machine-Vision Inspection Systems

During the manufacturing process, the bead of structural adhesive is inspected by machine vision to verify the presence and the quantity of adhesive in critical regions (see article, page 87). As a result, it was necessary to select a material that has high visual contrast with the pen body so the vision system can process the image. In fact, the final material selection was partially based on this requirement, since the competing material had very little contrast with the black print cartridge.

Mechanical Properties

Mechanical properties are primarily determined by the adhesive type and the degree of cure developed during the assembly process. Because of manufacturing constraints and the asymptotic nature of chemical reactions, it is rarely possible (or even desirable) to obtain 100% cure. In practice, the adhesive is cured to less than 100% because the desired level of mechanical and chemical properties can be obtained under those conditions.

To select the proper structural adhesive for the color print cartridge, several thermoset systems were evaluated. All of them were fast, thermal-cure systems typically used in the electronics industry. The primary differences between the competing systems were the type of catalyst and the level of additives, fillers, and adhesion promoters. These different additives provided a range of adhesion levels, solvent resistance, cure rates, and other characteristics.

A uniform layer of adhesive is more critical for the color print cartridge than for the monochrome application. This is because the dispensed bead on the color cartridge is narrower and therefore the probability is higher that an adhesive defect

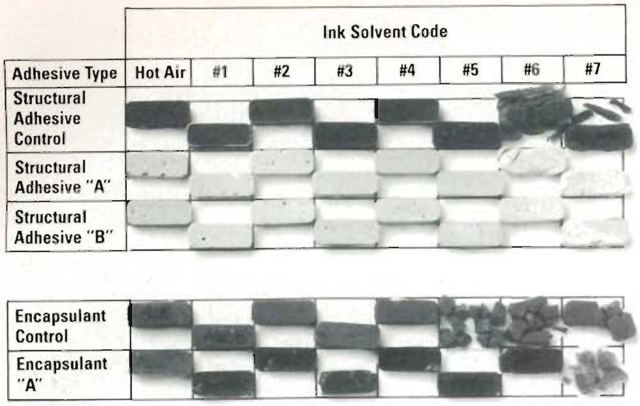


Fig. 1. Adhesive test blocks after accelerated stress tests.

will allow ink leakage between colors or to the external environment. The narrower bead widths also make it necessary to have higher adhesion strength on a unit-area basis. In the three-channel design, no extra room is available to lay down additional beads to provide higher adhesion. As previously mentioned, this initial adhesion had to be maintained as much as possible throughout the life of the print cartridge. Adhesion retention is a direct function of the cleanliness of the substrate (cartridge), the degree of cure, and the effect of long-term interactions with the ink.

The encapsulant materials that we investigated included two different chemical families. The material used on the original monochrome cartridge has some advantages in terms of good adhesion to the printhead. However, its chemical resistance is not great enough to withstand the new ink chemistries introduced with the color print cartridge. The new encapsulant has better chemical resistance even though it is slightly softer and has lower adhesion than the earlier material. This encapsulant survived the rigorous stress tests described above, which destroyed the previous material.

Interaction with Ink Components

Many of the adhesives met all of the performance requirements immediately after cure, but it was crucial to determine how the original material properties were degraded after exposure to inks and to ink components. To evaluate the chemical interactions, small rectangular blocks of each adhesive were poured, cured, and then exposed to ink under various environmental conditions.

As shown in Fig. 1, the test blocks revealed significant information about how the materials performed after immersion. Information gathered from this test and others enabled us to make two critical determinations: (1) Did the ink leach sufficient constituents out of the adhesive to affect ink quality?, and (2) Did the adhesive absorb sufficient ink components to significantly affect the mechanical and dimensional properties of the adhesive?

In some cases, the solvent components of the ink leached polymeric constituents from the adhesive, causing the ink to become contaminated and the adhesive to lose weight. In other cases, weight gain occurred because critical ink components were absorbed by the adhesive and depleted from the ink. In both cases, it proved necessary to evaluate the interactions by performing print quality tests.

Mechanical degradation of the adhesive was also caused by ink interactions. These effects were exhibited as adhesive swelling, loss of hardness, stress cracking, and crazing. Again, the largest factor here was material type. Postimmersion push tests were used to verify adhesion and integrity of the structural adhesive when tested on cartridge bodies.

Dispensing System Design

Applying structural adhesive and encapsulant to the color print cartridge presented significant design challenges compared to the original DeskJet print cartridge application. The trichamber design of the color cartridge and the two-piece assembly process placed more stringent demands on the dispensing systems. This provided the opportunity to advance our capabilities in small-volume dispensing technology and allowed us to build upon our previous manufacturing experience with inkjet products. After searching for outside vendors that could meet the requirements, it became obvious that we would need to design tools in-house to meet the required degree of accuracy. Inkjet technology has continually pushed the limits of standard adhesive technology and dispensing requirements. This new opportunity demanded that we design superior dispense systems that would lend themselves to our unique applications and allow us to leverage those capabilities into future manufacturing processes.

Structural Adhesive Dispensing Requirements

As mentioned earlier, the structural adhesive had the dual role of bonding the printhead to the cartridge and maintaining physical separation between the three ink channels and between the ink channels and the outside world. These functions had to be accomplished in an area that is no larger than that available on the original monochrome cartridge used in the DeskJet family of printers. Compared to previous products, the required bead width was approximately one-third smaller and the placement tolerance was about two-thirds smaller.

Encapsulant Dispensing Requirements

The encapsulation process is also more stringent than its predecessors. Previous applications controlled only encapsulation height and encroachment onto the orifice plate. However, to permit a different sealing mechanism in the printer service station, the color cartridge requires control on all sides of the dispense pattern. In addition to controlling orifice plate encroachment (for proper printer wiping) and height (to prevent crashing into the paper), the color cartridge has the additional constraint of maintaining a "free" area outside the encapsulation zone to allow access by the printer service station. This means that the process specifications are a factor of two tighter than what had previously been required for encroachment as well as requiring dimensional control in five directions (both sides, both ends, and height) instead of the previous two. The final problem for the dispensing system was that the cartridge body is assembled from two pieces—a nosepiece welded to a body. This provided the challenge of an increased tolerance stackup when the part was presented to the dispenser and made it likely that the dispensed surface would not be flat. A background concern affecting all of the others was the knowledge that a steep production ramp would necessitate low cycle times and high reliability.

Tooling Objectives

The primary objectives for the tool included controllable adhesive volume delivery, a multiaxis closed-loop control system, and a system to locate cartridge position. Means had to be provided to locate and calibrate the dispense tip so the system could perform without operator intervention.

Adhesive dispense systems from the electronics and automotive industry were evaluated, site visits were conducted, and trade show information was digested. None of the systems we evaluated would provide the tolerances or multiaxis synchronization that was required. While some of the dispensers in the automotive industry had the desired closed-loop features, the differences in scale were just too large to bridge. It was ultimately concluded that no other applications required the same combination of precision, speed, and small dispense volume.

Production Equipment

A CNC-type controller was selected to provide the required four-axis synchronization. Cartridge location is determined by position sensors, allowing us to locate the part in space in all three axes. Dispense tip location is determined by multiplexing the vision engine that was already in place for online inspection of the dispense pattern. With both the cartridge and the dispense tip located in space, the dispense pattern can be adjusted for each individual cartridge. We selected a controllable dispense mechanism that is force-fed from a pressurized syringe. This solution provides most of the benefits of true positive displacement even though it has the drawback of not accommodating viscosity changes in the adhesive. Fig. 2 shows the adhesive pattern.

The final system design meets all of the original demands that were imposed by the color print cartridge. It also goes a long way toward advancing our understanding of dispensing technology. Finally, the system provides us with the capability of modifying the design in the future to provide true positive-displacement dispensing for other applications that require similar precision.

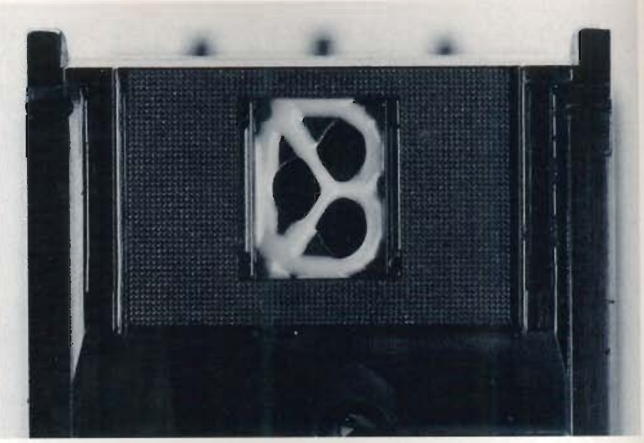


Fig. 2. Adhesive pattern dispensed by the production equipment.

Acknowledgments

We would like to thank Melanie Feder for her invaluable assistance in evaluating many of the adhesive systems, providing the samples shown in Fig. 1, and consulting on various aspects of materials compatibility testing. We also want to thank Gary Lutnesky for his direction and help in designing the dispense system.

Machine Vision in Color Print Cartridge Production

In production of the tricolor print cartridges for the HP DeskJet 500C and DeskWriter C printers, machine vision is used for filter stake inspection, adhesive and encapsulant dispenser calibration, structural adhesive inspection, and automatic print quality evaluation.

by Michael J. Monroe

Machine vision can be described as the synthetic acquisition, analysis, and interpretation of images, usually to provide feedback and control for some automated activity. Machine vision has been implemented through the marriage of video camera and display systems to computer technology, and it is often associated with some form of artificial intelligence. Most machine vision applications entail massive data reduction from the millions of bits that represent the images to often a single bit indicating a pass or fail status.

Machine vision is usually used for machine or robot guidance, defect identification and classification, part and assembly alignment, and feature measurement. Automated production environments are the ideal home for machine vision. There it can be applied to relatively simple, repetitive tasks, and cycle time is of critical importance. These applications are distinguished from the more generic digital image processing used in areas such as astronomy, bioscience, and satellite image enhancement, for which the algorithms tend to be very CPU-intensive and execution time is of less importance.

Increased quality is usually the primary motivation for automating a task with machine vision. Machine vision can eliminate the subjectivity often found in manual inspection operations. Quality can also be increased through reduced inspection error rates by eliminating operator fatigue. The improvements in quality that machine vision can help attain may be vital to the long-term competitiveness of a manufacturing operation.

Illumination and Optics

No discussion of machine vision would be complete without emphasizing the importance of illumination and optics. These aspects are critical to nearly all machine vision applications, and indeed the viability of a particular application may hinge upon the design of the illumination and optical systems. Careful design of the illumination system for a particular machine vision application can provide enhancement of contrast or of certain features of interest in the field of view, or it can be used to filter out features that may confuse the algorithm. One obvious advantage of image enhancement through illumination is that it operates on the entire image instantaneously, much faster than any digital image processing. Techniques such as light and dark field illumination can greatly improve the contrast between features of interest and the background. Linear or circular polarization of the illumination or application of on-axis or off-axis illumination can mitigate the effects of specular reflection from metallic or polished surfaces, which can often saturate the imaging sensor within the camera, causing the resultant image to be of little use. In some applications there is no usable contrast between the features of interest and the background, and imaging using illumination in the visible wavelengths is impossible. However, ultraviolet illumination, to which most cameras have reduced sensitivity, can induce some materials to fluoresce in the visible region of the spectrum, thereby providing usable images. Some machine vision applications require only the information that is contained in the outline or silhouette of the object of interest. Backlighting or placing the object between the camera and the illumination source can provide images of such high contrast that they are nearly binary in nature.

Design of the optical system is equally important. CCTV or C-mount lenses, commonly employed with standard video cameras, are often used in machine vision. They are inexpensive, but they provide resolution and contrast that are marginal or inadequate for many applications. Lenses designed for use with standard 35-mm cameras or photoenlarging lenses are somewhat more expensive, but they provide much higher resolution and contrast, and the control of aberrations such as distortion and field curvature is much better. For applications that require extremely high resolution and magnification, micrographic lenses are usually the best choice. The key parameters to be considered during the design of the optical system are the working distance or the distance between the lens and the object, the magnification, and the focal ratio. The working distance and the required magnification are used to determine the focal length of the lensing system, and the focal ratio is a function of the available illumination. Other considerations such as shock and vibration and rigidity of the mounting systems are also very important.

Software

The often crucial nature of the illumination and optical systems design should not overshadow the design of the software that is to be run on the machine vision engine. During the development of most machine vision applications, the majority of the time is devoted to the design, coding, and debugging of this software. The software for a typical application can be broken into five segments. First is image acquisition, which entails synchronization of the video source and then digitization and storage of the image data into frame buffer memory. The most common video source is a standard RS-170 monochrome camera, which transfers the data representing a full frame in 33 milliseconds. After acquisition of the image, some sort of enhancement of the features of interest is usually done. This may consist of high-pass or low-pass convolution filters for treatment of the edges of the features, or morphological filtering, which can eliminate noise pixels in an image. Image segmentation usually follows to provide some means of separating the features of interest from the background or other extraneous parts of the image. Binarization or thresholding of the image is a segmentation technique used to convert an image represented by many gray levels to one consisting only of regions of pure black or pure white. This method also greatly reduces the amount of data that must be processed during the analysis of the image. Feature extraction is then used to derive data on the details of features of interest that will be used during the interpretation phase of the algorithm. Analysis of the gray level sums of the pixels in all of the rows and columns of an image results in profile information such as the position, size, or shape of features. Template or pattern matching uses a previously stored model to locate the position of a matching model in the acquired image. Connectivity analysis provides detailed information on linked areas within a binary image. Morphological analysis can provide data on the shapes of various features of interest, in addition to its usefulness as a noise filter. Finally, all of the acquired data representing the image must be interpreted so that some useful result can be found. This may take the form of calibration or position coordinates that can be used for machine guidance, or it may simply be the pass or fail result of an inspection task.

Machine Vision in InkJet Component Production

Hewlett-Packard has used machine vision for years to improve efficiency and quality in the manufacture of integrated circuits, printed circuit assemblies, calculators, thermal inkjet printheads, and many other products. The Inkjet Components Division has been a leader in the incorporation of this technology into the production processes of its products. Beginning in 1983, machine vision has been used in the final assembly of the HP ThinkJet print cartridge to inspect for defects such as poor structural adhesive placement and leaks. In addition, samples from every print cartridge are analyzed using machine vision to screen for various print quality defects. These machine vision applications were further refined and new ones were developed for the manufacture of the HP DeskJet print cartridge. Machine vision is used to assist very high-precision part alignment and placement machines in the attachment of orifice plates to the thin-film substrates of the printhead assembly and in the placement of the printhead assembly onto the plastic print cartridge body.[1] In addition, a new fully automatic high-speed print quality tester was developed using machine vision to inspect print samples of 100 percent of the print cartridges manufactured.

Color Print Cartridge Production

In the early 1980s, when general-purpose machine vision engines were first made available, many different manufacturers offered products that were similar in function but very different with respect to instruction sets and software development environments. Since that time, there has been a shakeout in the marketplace, and fewer different machines are being offered today. However, the products that remain still tend to be very proprietary in nature, and little if any effort has been made to create the type of standards that exist today in the computer market. This lack of standardization and especially the preponderance of proprietary instruction sets can greatly reduce the efficiency with which new machine vision applications can be developed. Therefore, it is of great benefit to choose one product that has adequate capability for most if not all applications. This benefit of standardization is particularly important in the manufacturing environment, where machine vision applications tend to proliferate and support becomes a significant issue.

For the HP DeskJet 500C/DeskWriter C print cartridge production line we have chosen an engine that offers a range of optional features and capabilities, but uses a common instruction set and software development and debug environment throughout. In a similar vein, a single line of very high-quality photoenlarging lenses has been selected to provide several focal lengths and focal ratios that are suitable for most machine vision applications.

Filter Stake Inspection

Because the printhead for the Deskjet 500C printer is a tricolor printhead it has a separate chamber for each of the cyan, magenta, and yellow primary colors. At the bottom of each of these chambers near the nose of the print cartridge there is a stainless-steel filter screen that is heatstaked to a standpipe. The filter staking process is a critical one, and machine vision has been incorporated to ensure that every print cartridge body coming from the filter staker tool has three filters that are properly staked to the standpipes of the print cartridge body. Each filter is inspected for presence, proper centering on the standpipe, and an adequate weld ring indicating satisfactory attachment to the standpipe. The filter staker consists of an individual staking station for each of the three filters, and each of these stations is equipped with camera, optics, and illumination to enable inspection immediately after completion of the staking operation (see Fig. 1).

The filter stake inspection process is a good example of a machine vision application in which optics and illumination determine the viability of the process. Because of the flow characteristics of the plastic material used in the print cartridge body, relatively little of the material is drawn up into the weave of the filter screen during the heatstaking process. As a result, images that displayed little or no contrast between the weld ring and the filter were all that could be achieved with nearly on-axis illumination. It was found that contrast could be enhanced somewhat by increasing the angle of illumination from the normal to the filter. However, this angle was limited by the shadowing caused by the walls of the print cartridge body. At this point, contrast was still inadequate for reliable imaging, and further development

Fig. 1. The filter stake inspection station uses off-axis illumination and polarizing optics.

was required. It was determined that although the filter screen material is relatively rough and provides reflection that is primarily diffuse in nature, there is also a specular component that tends to saturate the imaging sensor in the camera and thereby further reduce contrast. Therefore, linear polarization of the illumination source is used to mitigate the effects of specular reflection and produce images adequate for a robust inspection process. The angular orientation of the filter screens greatly affects the reflectance of the material, and as a result, the images vary from brightness levels too low to be of use to levels so high as to cause saturation of the imaging sensor. In most machine vision applications, the camera's automatic gain control (AGC) is disabled so that the gray levels digitized by the vision engine provide a more accurate representation of the object. However, it was found that the camera itself could be made to cope with the wide variations in brightness simply by reenabling the AGC.

The inspection algorithm is based upon gray-level row and column profiling for determination of filter centering on the standpipe, and gray-level pixel sums and ratios of sums to ascertain filter presence and gauge the continuity of the weld ring. The inspection based upon the analysis of gray levels is very robust and provides false-pass and false-reject rates that are nearly zero. In addition, image acquisition and processing are extremely rapid, and a single machine vision engine can support all three of the inspection stations. At the completion of the inspections, the test results are sent to the PLC (programmable logic controller) that controls the filter staking process, and that data is then transferred to a failure off-load station via pallet code blocks.

Adhesive and Encapsulant Dispensing

The print cartridge for the HP DeskJet 500C printer contains three inks of different colors, and it is critically important that complete separation between these inks be maintained at all points throughout the print cartridge. Any ink mixing will result in contamination of the inks and of the colors that they produce on the printed page. The structural adhesive that bonds the thin-film printhead to the nose of the print cartridge plays a vital role in providing the required ink isolation. Because all three inks are channeled to the same printhead, the tolerances associated with the placement of the pattern of structural adhesive are more restrictive than those of other thermal inkjet print cartridges. As a result, it was recognized that some means of providing an efficient and accurate calibration of the exact position of the needle tip of the adhesive dispenser was required. A similar requirement existed for the encapsulant dispensing process. Machine vision was chosen as an aid to ensure accurate placement of the structural adhesive and encapsulant by providing the dispenser system controller with accurate x, y, and z coordinates of the location of the dispenser needle tip.

Each of the dispenser stations is equipped with two orthogonally positioned cameras and associated optics (Fig. 2). During the calibration process the positioning system moves the dispenser needle to a calibration position so that images from both of the cameras can be captured by the machine vision engine. Through analysis of both of the images the vision engine can determine the x, y, and z coordinates of the dispenser needle tip in pixel space. Then the coordinates in pixel space are converted to coordinates in the coordinate space of the dispenser positioning system using calibration coefficients previously stored in nonvolatile memory of the machine vision engine. This position data is then sent in the form of offsets to the dispenser system positioning controller via an RS-232-C datacomm link. The calibration process is fully automatic and requires operator assistance only for initiation of the procedure. It is normally performed only at the beginning of a shift or when a dispenser needle has been changed.

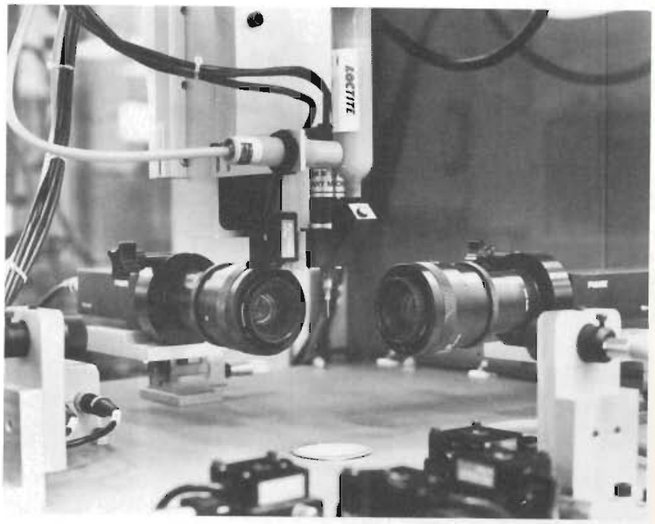


Fig. 2. The adhesive and encapsulant dispensing stations are equipped with two orthogonally positioned cameras using backlighting to determine the position of the dispensing needle tip accurately.

All of the data necessary to determine the precise position of the dispenser needle can be inferred from the profile or silhouette of the needle tip. This provides an ideal opportunity for backlighting or placing the object to be imaged between the illumination source and the camera. Backlighting typically produces an image of extremely high contrast, and often the image is nearly binary with the object appearing dark against a bright background. Since the required accuracy of the machine-vision-based calibration system is very high, a significant amount of magnification is required to achieve the necessary resolution. An appropriate photoenlarging lens with adequate extension was selected to provide the desired field of view.

The machine vision engine uses an edge-enhanced pattern matching technique to locate the dispenser needle tip in the field of view to subpixel accuracy. The template or model describing the salient features of the object to be located is stored in the nonvolatile memory of the vision engine during a setup procedure. A unique model for each of the cameras is stored. These models are then used during each subsequent calibration procedure to determine the locations of the desired features in the two images. Also during the setup procedure, each of the cameras is calibrated using a precision reticle grid placed in precisely the same position as the dispenser needle. Nine intersections on the grid are then used as calibration points so that an array of coefficients can be produced and then used to convert coordinates in pixel space to machine coordinate space. The machine vision engine has dedicated RS-232-C datacomm ports connected to the adhesive dispenser system controller and the encapsulant dispenser system controller. After the offsets in machine coordinate space have been computed by the vision engine, they are sent to the respective controller via these links. Since these calibration procedures are performed on a fairly infrequent basis, speed of execution is not of paramount concern. As a result, the two dispenser systems share one machine vision engine with the structural adhesive inspection station. The automatic calibration process has proved to be robust and to provide precise and repeatable dispenser needle positioning data to the dispenser system controllers.

Structural Adhesive Inspection

Although the machine-vision-based dispenser calibration process provides an efficient means of compensating for variation in needle tip positions, it cannot prevent other possible defects in the structural adhesive pattern. As previously stated, the integrity of this adhesive pattern is vital to the proper functioning of the print cartridge. Therefore, an automatic inspection station was developed using machine vision to ensure that each print cartridge body has an acceptable and accurately placed pattern of structural adhesive before reaching the head attach station. Because the adhesive is very soft and easily disturbed after leaving the dispenser station, it was imperative that a noncontact means of inspection be used. The pattern of structural adhesive for each print cartridge is visually inspected for proper centering and area of the adhesive and for proper centering and area of each of the three channel openings. In addition, the pattern is inspected to ensure that the bead of adhesive is continuous and free of sections that are excessively narrow or wide.

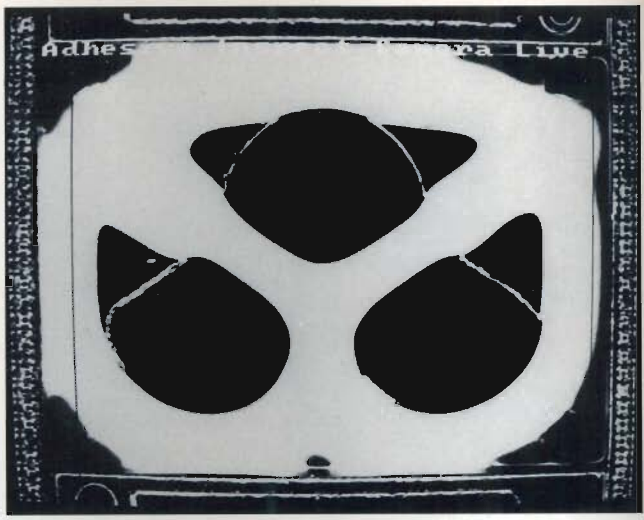
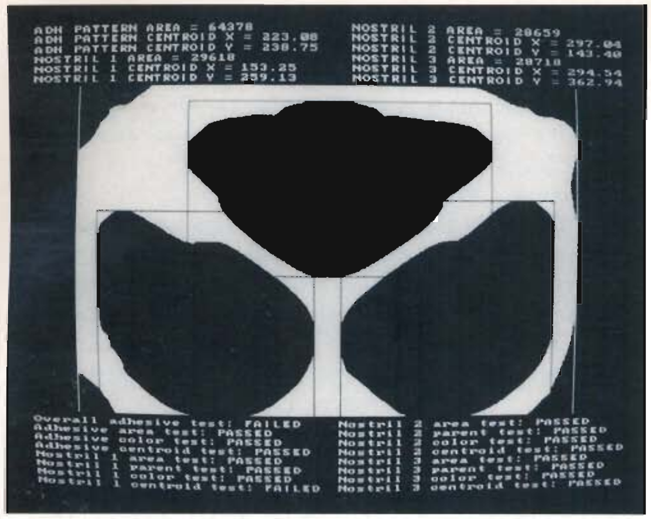


Fig. 3. Unprocessed image of the structural adhesive pattern.

The structural adhesive that was originally to be used provided virtually no contrast when placed on the black plastic nose of the print cartridge and illuminated with light in the visible portion of the spectrum. However, when ultraviolet light was used to illuminate the adhesive, fluorescing compounds contained in it caused it to appear light blue against the black background of the nose. This technique provided some usable contrast, but it was marginal and not likely to succeed with the variabilities commonly found in a production line environment. A new adhesive was selected. The new material provides images of extremely high contrast and allowed the development of a very robust inspection process. Lighting for this application is provided by a standard fluorescent ring lamp, which supplies adequate illumination that is very uniform across the field of view. The standard photoenlarging lens provides excellent, zero-distortion images (Fig. 3).

The most serious defect in the structural adhesive pattern occurs when an insufficient amount of adhesive has been placed by the dispenser station, and a break or discontinuity occurs in the bead. Continuous or connected regions in the image are most effectively evaluated through the application of connectivity analysis. Because the adhesive provides images of extremely high and consistent contrast, binarization and the subsequent connectivity analysis have proved to be a very robust inspection technique. Indeed, the images are of such quality that adaptive thresholding, which is usually required to compensate for variations in contrast and illumination, is not necessary. This results in a decrease in the overall cycle time for the process. Morphological filters are applied to the binary image to remove random noise pixels that could taint the connectivity data, and to reduce the width of the bead image so that portions that represent insufficient adhesive will actually separate and can be easily identified. The database produced from the connectivity analysis furnishes information such as area, centroid, and perimeter of the connected regions found in the image, and a description of the hierarchical relationship between those regions. Much of this data is easily compared with test limits to determine the adequacy of the adhesive pattern (see Fig. 4). However, because of the tight tolerances associated



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ADH PATTERN AREA = 64378                NOSTRIL 2 AREA = 28659
ADH PATTERN CENTROID X = 223.08         NOSTRIL 2 CENTROID X = 297.04
ADH PATTERN CENTROID Y = 238.75         NOSTRIL 2 CENTROID Y = 143.40
NOSTRIL 1 AREA = 29618                  NOSTRIL 3 AREA = 28718
NOSTRIL 1 CENTROID X = 153.25           NOSTRIL 3 CENTROID X = 294.54
NOSTRIL 1 CENTROID Y = 259.13           NOSTRIL 3 CENTROID Y = 362.94

Overall adhesive test: FAILED           Nostril 2 area test: PASSED
Adhesive area test: PASSED              Nostril 2 parent test: PASSED
Adhesive color test: PASSED             Nostril 2 color test: PASSED
Adhesive centroid test: PASSED          Nostril 2 centroid test: PASSED
Nostril 1 area test: PASSED             Nostril 3 area test: PASSED
Nostril 1 parent test: PASSED           Nostril 3 parent test: PASSED
Nostril 1 color test: PASSED            Nostril 3 color test: PASSED
Nostril 1 centroid test: FAILED         Nostril 3 centroid test: PASSED
```

Fig. 4. Structural adhesive pattern image after processing and analysis, showing test data and results.

with the adhesive placement and the positioning errors inherent in the pallet lift and index mechanism, it is essential to locate a feature on the nose of the print cartridge with which to compare the adhesive pattern location. The central channel opening in the nose is located using edge-enhanced pattern matching before the connectivity analysis so that its position can be used as a reference in the subsequent tests.

Automatic Print Quality Tester

The quality of the HP DeskJet 500C print cartridges leaving the production line is of the utmost concern. This concern precipitated the development of the automatic print quality tester, on which 100 percent of the print cartridges manufactured are tested. The automatic print quality tester is the final arbiter of print cartridge quality, and it is its responsibility to provide information regarding print cartridge performance so that the defective ones can be culled from those that are acceptable at the end of the production line. The automatic print quality tester is capable of detecting a wide variety of print cartridge defects. It is a fully automatic tester that receives print cartridges seated in nests on a rotary table, fires the print cartridges so that test patterns are printed on paper, and then uses machine vision to examine and evaluate the printed patterns to detect any possible defects in the print cartridges. At the completion of the tests for a given print cartridge, test results in the form of fail codes are both stored locally and sent to a data collection system so that yield and defect summary reports can be prepared. The local database can be interrogated using online utilities, and yield and defect distributions can be displayed in near real time.

The automatic print quality tester uses a relatively straightforward optical and illumination design that incorporates high-quality macroscopic lenses and fiber optic ring illuminators (Fig. 5). The challenge was how best to deal with the cyan, magenta, and yellow primary colors. Standard color imaging techniques using a color video camera with RGB outputs were considered but rejected because frame storage memory requirements were tripled relative to those for monochrome imaging, and most color cameras provide significantly reduced spatial resolution. In addition, before meaningful color image analysis can take place, the contents of the frame buffers that contain the gray levels representing the red, green, and blue video camera outputs must be combined and converted into a more useful color coordinate system such as HSI (hue-saturation-intensity). The time required to make these conversions in software was prohibitive with respect to the overall cycle time of the tester. Because nozzle defects and not hue shifts are the most common defect types, it was decided that true color imaging was not required, and an approach using color filters was taken. If the machine vision engine is presented with images of high enough contrast with the ink appearing dark on the white paper background, it can easily perform the required analyses to determine the health of the print cartridge. The cyan and magenta primaries provide usable contrast without any special optical techniques, but the yellow ink is nearly invisible to the CCD camera. By placing a blue interference filter in front of the camera lens, the yellow test patterns are made to appear dark enough to provide usable contrast in the image. A similar enhancement is afforded by a green interference filter on the camera that is used to image the cyan and magenta test patterns. It greatly increases the contrast of the magenta patterns, but has little effect on the cyan. This technique in effect reduces the number of images that must be acquired for each test pattern from three to two, and it eliminates the necessity of time-consuming color coordinate conversions.

As previously mentioned, the automatic print quality tester ensures the quality of the print cartridges leaving the production line. Special test patterns were developed to reveal the several types of possible print cartridge defects. These test patterns help ensure that the machine vision engine can provide an effective screen for defective print cartridges. These patterns are printed by the print cartridge under test, and after completion of the printing phase, the paper is advanced (Fig. 6) until the test patterns are within the fields of

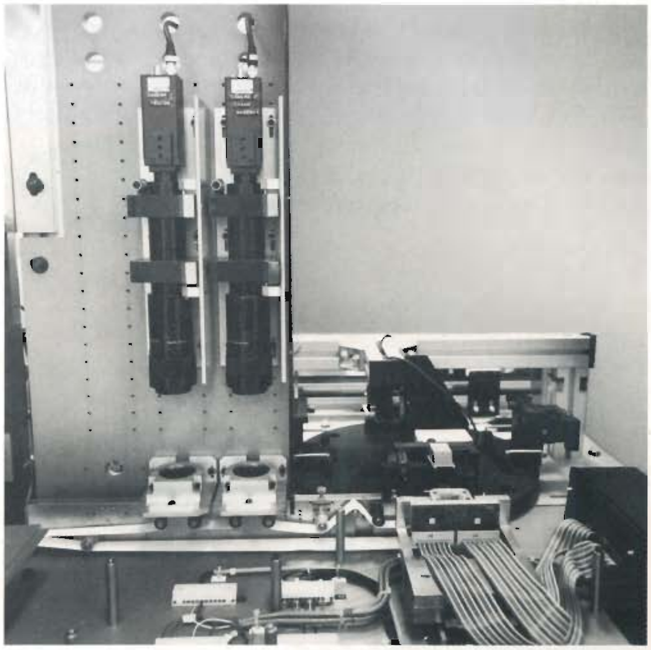

Fig. 5. A view of the automatic print quality tester showing the illuminators, cameras, optics, rotary table, and print cartridge nests.

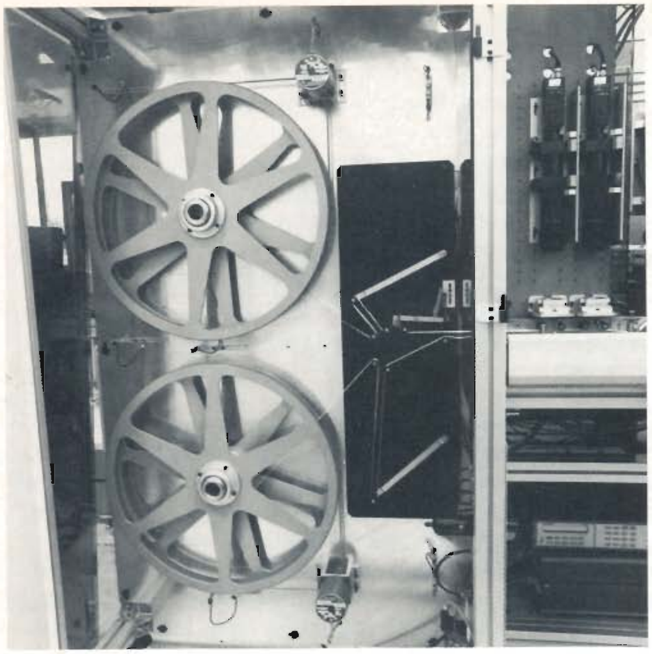

Fig. 6. A view of the automatic print quality tester showing the paper feed and take-up reels and tension arms.

view of the cameras. Signals sent between the paper motion controller and the machine vision engine synchronize the acquisition of all of the test pattern images. The machine vision engine then processes and analyzes the images using techniques such as row and column profiling, edge enhancement, and grey-level pixel sums to identify any defects present. At the completion of the image analysis phase, fail codes that represent any test pattern defects that may have been detected are sent to the HP-UX*-based system controller via an RS-232-C serial data link. Because of the physical separation between the cameras, and for efficiency and throughput considerations, during any given test phase the machine vision engine is evaluating the test patterns from two different print cartridges. It is the responsibility of the system controller to receive and sort the fail codes for these print cartridges properly so that all of the failure information for a particular print cartridge is associated with the bar-code number for that print cartridge. This failure data is then both stored in a local file and sent to the production line data collection system via a local area network. The automatic print quality tester has demonstrated that a fully automatic machine is capable of effective print quality assessment, and that it can ensure that the print cartridges leaving the production line are of the highest possible quality.

Conclusion

The high-volume production of thermal inkjet print cartridges requires many very accurately controlled and repeatable processes. Most of these processes are implemented using well-designed, high-precision automatic machines. Machine vision has played an essential role in the calibration, inspection, and control aspects of many of these processes, and it has helped ensure interprocess quality as well as the quality of the final product. Machine vision is a key ingredient in the further evolution of computer integrated manufacturing. As the technology continues to advance and the cost of its use continues to decrease, an ever-expanding number of applications will be found for machine vision.

Acknowledgments

Many different people deserve recognition for their efforts in the development and integration of machine vision into the production processes for the HP DeskJet 500C/DeskWriter C print cartridge. Thanks to Dennis So for his expertise in the development of the production line control and data systems. For their assistance in the development of the automatic print quality tester, thanks to Tim Hubley, Gary Lutnesky, and Steve Steinfield, its original designers, and Sang Bradley for the development of the system controller software. Thanks also to Bob Conder for the brainstorming that led to the development of the filter stake inspection process, and for his project leadership in keeping all of us pointed in the same direction.

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HP DeskWriter C Printer Driver Development

Running on the host computer, the driver provides all of the intelligent formatting, rasterizing, color matching, and dithering for this affordable black and color printer.

by William J. Allen, Toni D. Courville, and Steven O. Miller

A printer driver is a program that provides an interface between an application program and a printer. In the Macintosh and Microsoft® Windows environments, the application/driver interface is well-defined. This allows a single driver to serve all applications in a particular environment.

The HP DeskWriter C and DeskJet 500C printers use the same print cartridges and mechanical components to mark the page. Basic print modes and color imaging techniques are the same for both products. To improve clarity, this article focuses on the DeskWriter C (Macintosh) driver. Where appropriate, significant differences in the DeskJet 500C (Microsoft Windows) driver will be pointed out.

To be competitive in the marketplace, a low-cost printer manufacturer must provide drivers for the two most popular windowing environments, Microsoft Windows and the Macintosh operating system. Manufacturers of high-end printers can always include the widely used page description language PostScript® to guarantee support of the printer. However, including PostScript in a low-cost color printer like the HP DeskWriter C would be prohibitive, significantly increasing the price of the product.

The alternative is to build into the printer only the logic necessary to put the dots onto the paper fast enough to keep the mechanism busy. This requires the driver, running on the host machine, to provide all of the intelligent formatting, rasterizing (converting logical graphics objects to a bit image), color matching, and halftoning. This approach, of using the host machine's CPU power to create the raster image to be laid down by the printer, is the one that we take with the HP DeskWriter C.

HP DeskWriter C Printer Driver

The HP DeskWriter C driver is a program that sits between the user, the application, and the operating system as shown in Fig. 1. This diagram shows the major paths of communication and control managed by the driver.

The user creates a document using the application, then chooses Page Setup, causing the application to call the printer driver's Page Setup command. The printer driver puts up the Page Setup dialog box for the user and returns the modified page size and printer attributes to the application. The application can use this information to reformat the document for the new attributes.

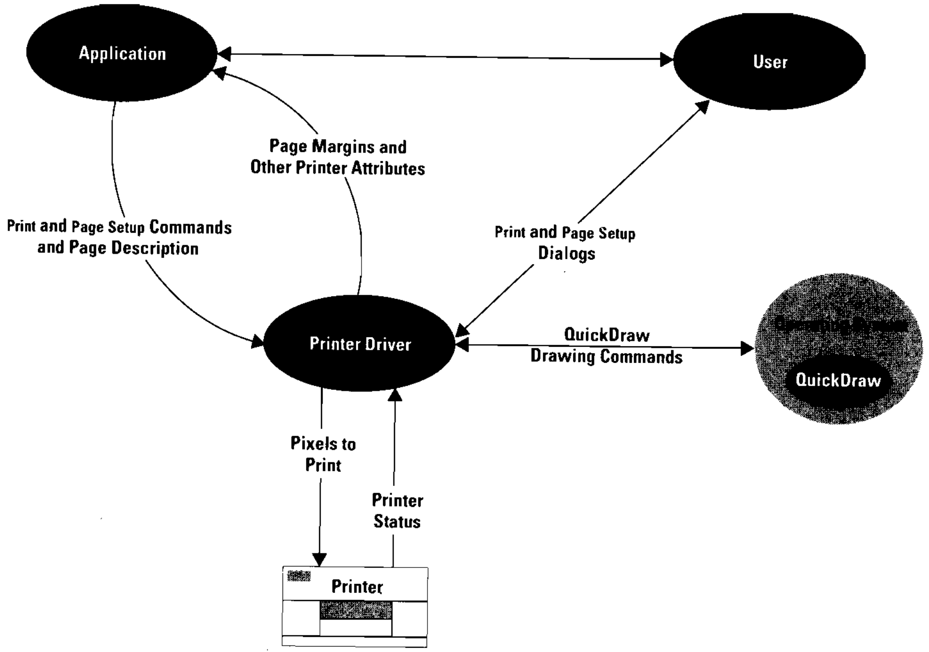


Fig. 1. Diagram showing the major paths of communication and control managed by the HP DeskWriter C printer driver. QuickDraw, the drawing command language of the Macintosh computer, is similar to GDI (Graphics Device Interface) in Microsoft Windows.

The user then prints the document by selecting Print, causing the application to call the printer driver's Print command. The printer driver puts up the Print dialog box for the user, and when the user is finished making selections the printer driver allows the application to send it a series of page descriptions. These page descriptions are a sequence of imaging commands which describe the page as a series of objects such as text, lines, circles, and raster images (PixMaps). The imaging commands are in QuickDraw, the drawing command language of the Macintosh (similar to GDI, or Graphics Device Interface, in Microsoft Windows).

Now the printer driver will immediately return control of the computer back to the user if the user has enabled background printing, or it will continue processing the print job in the foreground. In any case, the printer driver opens a communication path to the printer (either serial or AppleTalk), determines which print cartridge is installed in the printer, and then proceeds to use a combination of QuickDraw and its own built-in functions to rasterize the page description into a 150-dpi or 300-dpi PixMap.

This PixMap is then adjusted to compensate for the differences between the display and HP printing technology. This may include color matching for the current media, which attempts to make the printed colors appear the same as the colors on the monitor.

The PixMap is finally halftoned, which involves using various patterns of printed dots to simulate all colors that can be produced on the monitor. For instance, since the printer only has cyan, magenta, and yellow inks, it can't directly produce a purple dot. Purple is produced by printing a mixture of red and blue dots in a checkerboard pattern. Each red dot is made by printing a yellow dot on top of a magenta dot and each blue dot is made by printing a magenta dot on top of a cyan dot. This halftoned data is then compressed and transmitted to the printer.

While a communication path is open to the printer, the driver continuously receives status information from the printer so it can report error conditions such as "out of paper" or "wrong print cartridge installed" (e.g., the color print cartridge is installed, but the document only contains black data).

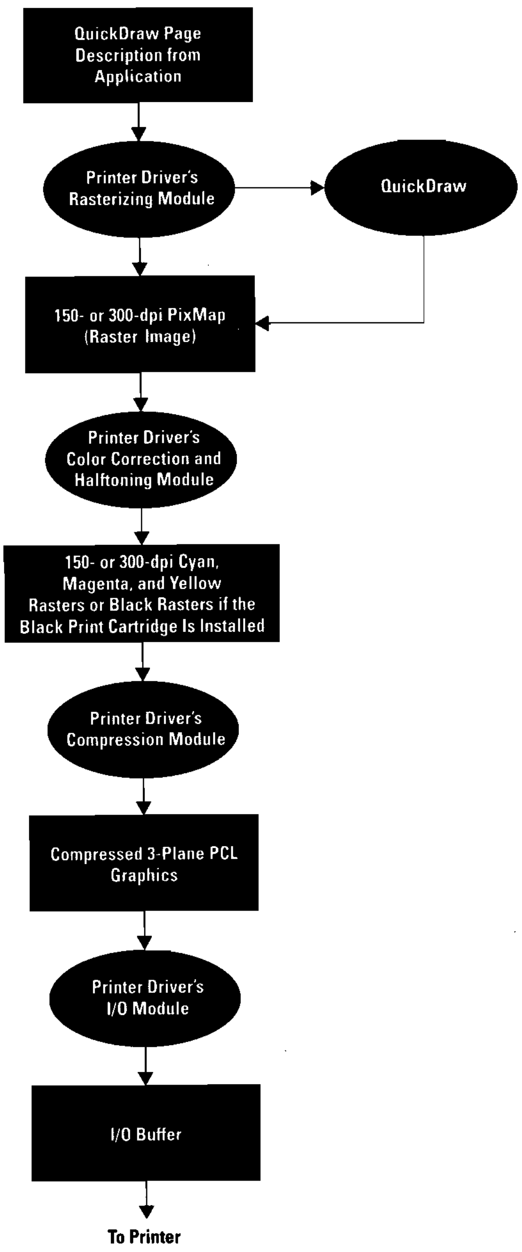


Fig. 2. This is the process for rasterizing a page in the HP DeskWriter C printer driver. The rectangles denote data and the ovals denote code.

Rasterization

Fig. 2 gives a closer look at how the printer driver rasterizes a page. The transformation from page description to PCL data takes place in several steps. The rasterizing module uses QuickDraw to do much of the work since the page description is in a set of QuickDraw commands anyway, but it replaces some of QuickDraw's functionality where necessary, such as in the rendering of text. Before Apple's System 7.0, QuickDraw did not provide scalable outline fonts, so the HP DeskWriter C rasterizer contains its own outline font renderer called Intellifont™ from AGFA Compugraphic. This provides all Macintosh users with access to high-quality scalable outline fonts for the most commonly used typefaces.

Because most computers have limited RAM, and rasterizing a 300-dpi page can take a lot of memory (up to 32 megabytes to represent a full color page), the driver usually rasterizes a portion of the page at a time in what is called banding. Banding is pictured in Fig. 3. The less available RAM the computer has, the more bands it takes to rasterize the whole page, and the longer it takes to complete the whole page, because there is a fixed overhead in rasterizing each band. Each object must be examined to determine if it falls within the band. If it does then it is rasterized (drawn) into the band. Otherwise, it is ignored (clipped). Objects that cross band boundaries must be rasterized for each band that they touch. For most common documents, banding adds little or nothing to the print time. Only for very complex documents that have a large number of objects, or for very low-memory conditions, which increase the number of bands, does banding significantly affect the time to rasterize the whole page.

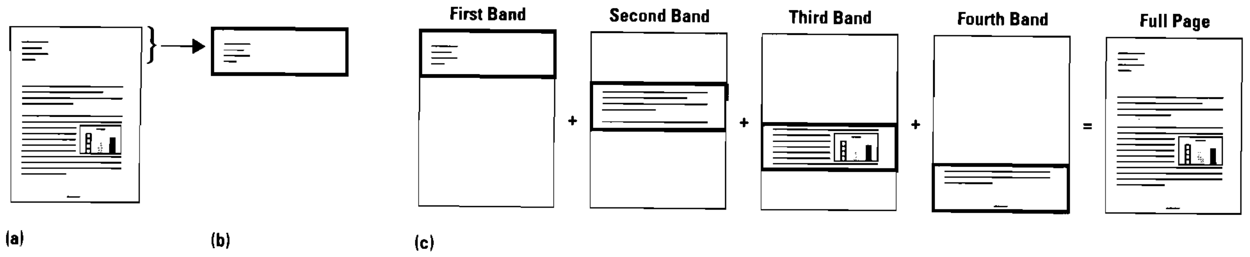


Fig. 3. When the host computer does not have enough available memory to rasterize a complete page, banding is used. (a) This page represents a 256-color document (8 bits per pixel). To rasterize it at 300 dpi would take about 8M bytes of memory. (b) If only 2M bytes of memory are available for rasterizing, then only a quarter of the page can be rasterized at a time. (c) The solution is to use the 2M bytes of memory to rasterize the top quarter of the page. As soon as this band is rasterized and its colors are adjusted, it is dithered, compressed, and transmitted to the printer. While this data is being transmitted, rasterization of the second quarter of the page begins, using the same 2M bytes of memory. I/O buffers ensure that printing continues while successive bands are being rasterized.

User Interface

This product had a wide range of human factors issues and challenges, all of which were analyzed, designed, and tested. The issues included defining a conceptual use model of the product, hardware design, and integrating aspects of color imaging into a simple driver interface.

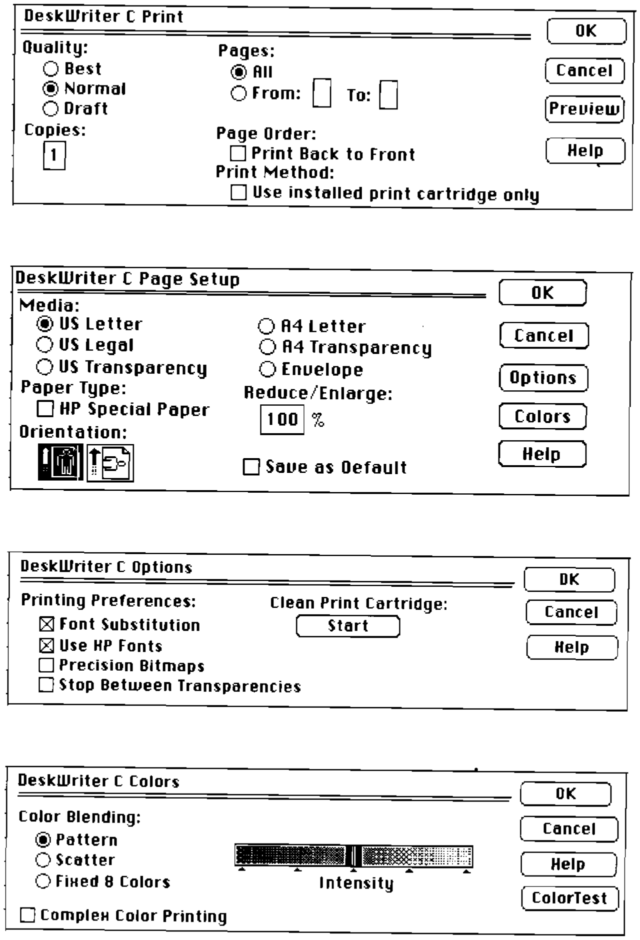
To design a product that meets the requirements of our users, we needed to find out who our users are. The key data point returned from market research was that the HP DeskWriter C should be designed for home and business users who do not currently use color, and who do not want to struggle with their computer or printer. Initial market research and human factors concept testing pointed strongly to the necessity for a user-friendly product with good print quality.

Usability studies and iterations of the user interface followed and continued for the next six months. Usability studies are more detailed than concept testing, and are designed to test users' reactions to specific aspects of a prototyped product. To test the user interface, subjects were asked to perform numerous printing tasks in a number of different scenarios. The users were questioned regarding verbiage, ease of use, and functionality offered. Our goal was to design a usable driver without compromising functionality and without creating confusion for less-technical users. We had three formal usability studies during the product design phase, which required a number of iterations to the driver's interface. The results from each study were published by our human factors engineer along with design recommendations for the next iteration. These design recommendations were based on the users' responses to questions, task completion successes or failures, and other observed data.

Dialog Boxes

Fig. 4 shows the final dialog boxes of the user interface. The first two dialog boxes, Print and Page Setup, are accessed from the menu bar. A key design objective was to make these screens as simple and uncluttered as possible. It was decided that only those functions for which frequent change was required would be in the two main dialog boxes. The more technical functions were put into the Colors and Options screens. This was done to decrease confusion for the typical user who would rarely have use for the added features. The defaults were chosen such that most users would not require the Colors and Options dialog boxes.

Features accessed through the Print dialog box are print quality, copies, page range, page order, and print method. Most of these printing features are common to other Apple drivers. Print Method: Use installed print cartridge only is a feature designed specifically for this product. When this checkbox is on, the alert messages prompting the user to exchange the print cartridge, which normally display when there is a discrepancy between the document content and the installed print cartridge, will not appear. This function is explained in further detail later in this section.



DeskWriter C Print
Quality:
○ Best
● Normal
○ Draft
Copies: 1
Pages:
● All
○ From: ☐ To: ☐
Page Order:
☐ Print Back to Front
Print Method:
☐ Use installed print cartridge only

DeskWriter C Page Setup
Media:
● US Letter
○ US Legal
○ US Transparency
○ A4 Letter
○ A4 Transparency
○ Envelope
Paper Type:
☐ HP Special Paper
Orientation:
Reduce/Enlarge: 100 %
☐ Save as Default

DeskWriter C Options
Printing Preferences:
☒ Font Substitution
☒ Use HP Fonts
☐ Precision Bitmaps
☐ Stop Between Transparencies
Clean Print Cartridge:

DeskWriter C Colors
Color Blending:
● Pattern
○ Scatter
○ Fixed 8 Colors
☐ Complex Color Printing

Fig. 4. HP DeskWriter C printer dialog boxes.

The Page Setup dialog box features are consistent with other Apple printers in that they allow the user to choose media type, print orientation, and a scaling value. The distinct features offered by the HP DeskWriter C are the HP Special Paper and the Save as Default checkboxes. The HP Special Paper checkbox is selected when printing on special paper. This causes the driver to adjust the way ink is put on the page so it is optimized for HP special paper. Save as Default offers the user the ability to save item states permanently in the Page Setup, Options, and Colors dialog boxes. For example, a user who always prints on U.S. legal-size paper need only select the paper size once, then check the Save as Default box, and click OK to exit the dialog box. US Legal will then be the new default, instead of the factory default, US Letter. This saves the user time by eliminating the need to enter the Page Setup dialog box for each document.

The Options dialog box, accessed by clicking the Options button in the Page Setup box, contains printing preferences and a Clean Print Cartridge button. This button, when selected, attempts to restore print quality if print becomes faint or dots are missing. This is done by activating a print cartridge priming algorithm in the printer.

Users who want more color capability can find it by clicking the Colors button. The color blending selections determine how dots of the three colors (cyan, magenta, yellow) are arranged on the page to create blended colors. Each of these selections produces slightly different results. Pattern produces faster output than Scatter and is recommended for simple solid-color graphics. Scatter takes longer to print and should be used for sophisticated color graphics, such as scanned images and photographs. Fixed 8 allows applications that support color on the Macintosh Plus, SE, Portable, and Classic computers to print the basic eight colors (red, blue, green, cyan, magenta, yellow, black and white). Fixed 8 is the only color blending setting available for these machines.

When the Complex Color Printing checkbox is on, the driver adjusts the printed colors to provide the best match in appearance to the screen. This capability is recommended for complex color graphics such as scanned images, photographs, and complex computer-generated artwork.

The Intensity slider allows the user to select the amount of color ink that is printed on the page. More ink increases the intensity of the images. Users in high-humidity environments may need to move the slider to the right to decrease the amount of ink on the page, since ink bleeding can occur with increased moisture in the air and on the paper. To assist the user in deciding which slider bar location creates the most desirable output, a color test was created. When the user clicks the ColorTest button, a one-page printout is provided that shows the effects of the intensity settings on text, simple graphics, and a complex color image. The ColorTest feature is designed to save the user time by eliminating the need for numerous experimental printouts to determine the best intensity setting.

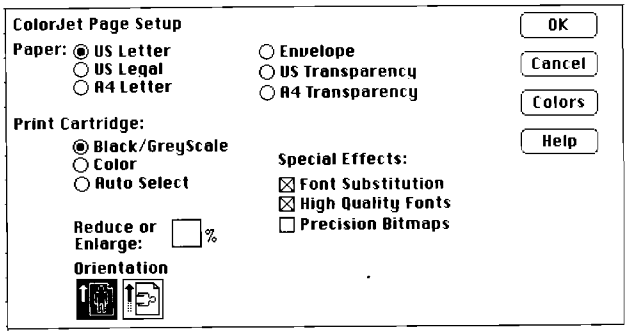
The Colors dialog box was created for the more sophisticated color user. The defaults were chosen such that output will be acceptable for the majority of print jobs. Pattern was chosen for its speed over Scatter and the assumption that most users would probably print simple color graphics. The middle setting in the Intensity slider bar is the default; it is designed to work best in most environments.

Print Cartridge Selection

The dialog boxes described above illustrate the user-driver interaction required to control the printer. In addition, it is necessary for the user to interact with the printer hardware by changing print cartridges. Because this is a completely new task to most customers, numerous prototypes were designed and tested before the final solution was created.

Fig. 5 shows one of the print cartridge swap/page setup prototypes that we explored. The three extra buttons labeled Color, Black/GreyScale and Auto Select were provided to give the user a choice of which cartridge to print with. If the user chose Black/GreyScale, the black print cartridge was expected to be in the printer, and the document would be printed in black. If Color was selected, the color print cartridge would be used. If the expected print cartridge was not in the printer, an alert message would appear prompting the user to insert the correct cartridge. If Auto Select was chosen, the document was scanned, and the user was prompted to insert the black print cartridge if only black was present or to insert the color print cartridge if color was present. With a multipage mixed document (black and color pages), the pages would be ordered so that all the black pages were printed first, followed by the color pages, eliminating the need to swap print cartridges more than once. The user was always given the choice of overriding the swap alerts and continuing to print with the current print cartridge.

Tests of this model produced both positive and negative results. On the positive side, users liked the control of selecting the cartridge type themselves, without getting swap alerts. Choosing Black/GreyScale to print a draft of a color document is one example of the control desired. On the negative side, this model required the users to go into the Page Setup dialog box before printing, which was often forgotten. Most subjects felt this extra step cumbersome and not "Macintosh-like."



ColorJet Page Setup

Paper: ● US Letter ○ US Legal ○ A4 Letter ○ Envelope ○ US Transparency ○ A4 Transparency

Print Cartridge: ● Black/GreyScale ○ Color ○ Auto Select

Special Effects: ☒ Font Substitution ☒ High Quality Fonts ☐ Precision Bitmaps

Reduce or Enlarge: ☐ %

Orientation

Fig. 5. A prototype HP Deskwriter C dialog box that was redesigned because user reactions during usability testing were mixed.

The final print cartridge swap/page setup model eliminates print cartridge choices from the Page Setup dialog box completely. Instead, the machine scans for color and displays an alert message when a mismatch between the cartridge and the document is found. With this model, the user need not go into the Page Setup dialog box at all. The final model is both easy to follow and gives users the control they want. Instead of having the user select which print cartridge to use, the driver is always in auto select mode. The driver scans the document for color. If none is found, it verifies installation of the black print cartridge in the printer. If the color cartridge is in the printer, the user is alerted to change the print cartridge. The same is done if a color document is being printed and the black cartridge is installed. If the user is printing a document with both black and color pages, the driver firsts prints the pages that can be printed by the installed print cartridge. When printing of those pages is complete, the driver alerts the user to swap the print cartridge, then continues printing the remaining pages. This minimizes the number of user interactions. The control provided by the former design is offered with this model by the Use current print cartridge only checkbox in the Print dialog box. When this box is checked, the driver will print all pages using the current print cartridge in the printer, and will not prompt the user for print cartridge swaps.

Print Modes

In general, print quality settings allow the user to trade print quality for print speed. Draft mode is fastest, and has the additional benefit of saving ink. Mode selection affects the resolution at which the page is rasterized and the timing and placement of the dots that are printed onto the page. The printer's firmware is responsible for managing the mechanism, printhead, and low-level dot control.

Imaging Resolution. Most of the time, HP DeskWriter C drivers operate at 300 dpi. For faster throughput at the expense of resolution, 150-dpi imaging is available as draft mode. Rasterizing at 150 dpi versus 300 dpi speeds up printing in several ways. First, the driver only has to draw objects at half the resolution. Second, at 150 dpi, it takes only one fourth as many bands to rasterize a page as it does at 300 dpi, because each band at 150 dpi represents four times as much page area as it does at 300 dpi (memory requirements grow as the square of the resolution). Third, the driver has one quarter the amount of data to halftone, compress, and transmit.

Dot Timing and Placement. The print cartridge contains three colors of ink: cyan, magenta, and yellow. For each primary color, sixteen nozzles are allocated. The nozzles for each primary are separated vertically (Fig. 6). This means cyan ink is always fired onto dry media. Magenta comes next, possibly overprinting cyan, and yellow follows.

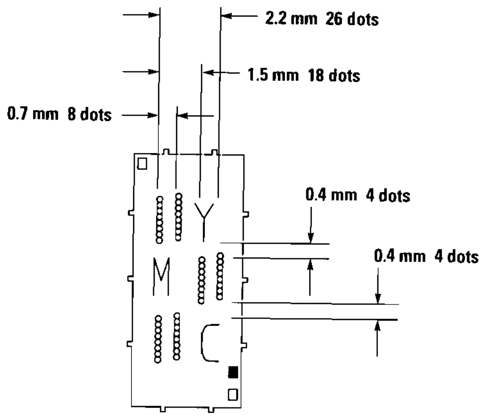


Fig. 6. HP DeskWriter C/DeskJet 500C printer orifice plate viewed from the paper.

In general, the printer can lay 16 rows of each color down at a time and then advance the paper 16/300 inch to lay down the next 16 rows of color. However, there are times when it is advantageous to lay the ink down more slowly while distributing the ink in a single raster row among several different nozzles in the printhead. This process is known as shingling (see Fig. 7). Using shingling, several separate print passes are used to lay the ink down, printing only a fraction of the dots in each raster row during each print pass. The paper is advanced slightly and then more of the pixels representing that row are laid down. The printer supports both 50% shingling and 25% shingling. 50% shingling lays down every other pixel in the row on the first pass and then the remaining pixels in the row on the second pass using a different nozzle of the print head. 50% shingling takes twice as many print passes to print a page and about 50% more time. It doesn't take twice as long, since every other dot is skipped during each pass, allowing the printer to increase the carriage speed without exceeding the maximum nozzle refire rate. Fig. 7 illustrates how the cyan ink will be printed with 50% shingling.

25% shingling is also available. It uses four times as many passes, laying down 25% of the ink in each raster row at a time.

Shingling provides several advantages. Printing each raster in several passes gives the ink a chance to dry before the adjacent dots are laid down onto the page. This is especially important when inks of two different colors are placed next to each other. Shingling allows the first color to partially dry and minimizes bleed (mixing) between the two colors. This is very important for printing on transparency media. Laying the ink down too quickly causes it to bleed and form puddles.

Shingling also distributes the printing of any single raster between two or more nozzles. This is useful for hiding inconsistencies between nozzles, such as a weak or missing nozzle, since it distributes the missing or weak dots among several rasters. A weak nozzle is not very noticeable when 25% shingling is used. Shingling also hides errors in paper feed accuracy in a similar manner.

When draft mechanical quality is selected, the printer will skip every other dot. This not only halves the amount of ink used to print the image, but also allows the printer to increase the carriage speed for the same reason it can when shingling.

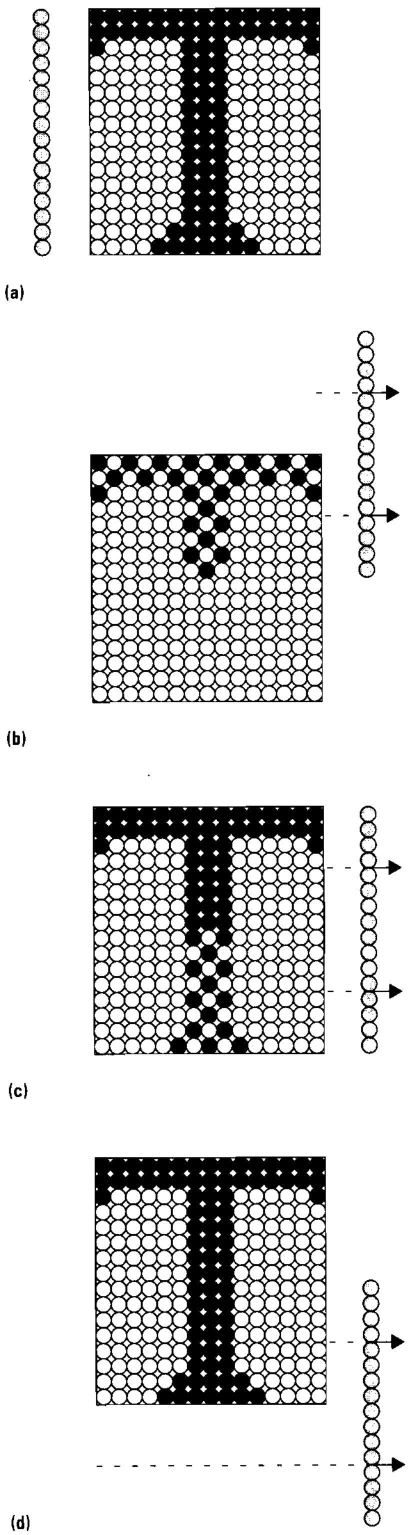


Fig. 7. Shingling is the process of laying down the ink dots in several passes, printing only a fraction of the dots in each raster row during each pass. (a) The 16 cyan nozzles spaced vertically 1/300 inch apart and a character to be printed. (b) During the first pass of the printhead, the first 8 cyan nozzles print half of the top part of the character. (c) During the second pass the first 8 cyan nozzles print half of the bottom part of the character while the second 8 cyan nozzles print the remaining dots in the top part of the character. (d) During the third pass of the printhead the second 8 cyan nozzles print the remaining dots in the bottom half of the character.

Resolution, shingling mode, and mechanical quality are mixed in various combinations to provide the user with three different quality modes for each of three types of media:

	Media Type		
Print Mode	**Plain Paper**	**HP Special Paper**	**Transparency**
Draft	150 dpi, no shingling, draft quality	150 dpi, no shingling, draft quality	Not supported
Normal	300 dpi, no shingling, normal quality	300 dpi, 50% shingling, normal quality	300 dpi, 50% shingling, normal quality
Best	300 dpi, 50% shingling, normal quality	300 dpi, 25% shingling, normal quality	300 dpi, 25% shingling, normal quality

Media. HP DeskWriter C and DeskJet 500 C printers are designed to provide good print quality on plain paper, special paper, and transparency media. The special paper and transparency media are specifically designed to work in the printers. They are available from Hewlett-Packard as CX JetSeries CutSheet Paper and LX JetSeries Transparency Film.

The ink performs differently on the three supported media types. When the user informs the driver which type of media has been selected, the driver takes this into account, and makes appropriate adjustments in the amounts of each ink deposited on the media.

Delivering high print quality on a wide range of plain papers is very difficult. As previously mentioned, print quality varies as a function of paper type and environmental conditions. The black print cartridge is the same one used by the HP DeskJet and DeskWriter printers. It is optimized to perform well over a wide range of plain papers. Similarly, the color print cartridge is designed to perform well on plain papers as well as on special paper. During development, print quality was tested on many different types of plain paper. From this large group, a small set of papers, each representing a significant subset of the universe of papers, was selected. Creating this manageable set of papers for initial evaluation of various inks, print cartridge architectures, and print modes proved valuable. Promising combinations could then be tested against the larger set to ensure robust performance.

Because we can control the design of the special paper, it is adjusted to accommodate the print cartridge. The special paper is coated on one side. The coating causes most of the colorants in the inks to be deposited near the surface of the paper after the inks dry. Concentrating the colorant near the surface increases the saturation of colors. The coating also reduces the sensitivity to environmental conditions. When using special paper, the user is less likely to need to adjust the intensity slider to accommodate environmental extremes.

The transparency medium consists of a plastic substrate and a special coating. The coating accepts the ink. Without the coating, ink would puddle up on the substrate and run together, forming large muddy pools. Like the special paper, the transparency is designed around the print cartridge.

Color Halftoning. Applications communicate with the driver through a stream of QuickDraw commands. These commands specify 24 bits of color for each 300-dpi pixel on the page. The printer can only place three bits of information at each 300-dpi print grid position—one bit for each primary ink. Color halftoning is the process that reduces the information from 24 to 3 bits per print position. By carefully controlling the placement of colored dots, myriad different colors are produced. Cyan, magenta, and yellow are halftoned independently. Cyan is reduced from 8 bits per pixel to 1 bit per pixel. Similar reductions occur for magenta and yellow.

Halftoning increases the effective color depth of the printer. The mechanism can put one of eight different combinations of the primary inks (cyan, magenta, yellow, red, green, blue, black, or white) on the paper at each 300-dpi print position. With halftoning, many more than eight colors can be produced. The increased color depth comes at the expense of spatial resolution. The halftoning techniques used in the HP DeskWriter C driver preserve 300-dpi edges. Spatially, the human visual system is much more sensitive to the edges of an object than to color shifts within the the object. Because the edges are preserved, the reduction in spatial color resolution is not offensive, and the increase in color depth allows complex images, such as photographs, to be reproduced well by the printer.

The user can choose between two color blending (halftoning) algorithms: *pattern* and *scatter*. Pattern is a dispersed ordered dither (Bayer's), while scatter uses a form of error diffusion.[1]

Pattern. The pattern algorithm is the default halftoning algorithm. It is a form of ordered dither. It does a good job with almost all types of data, but is best suited to simple graphics composed of large homogeneous regions. Computationally, it is much simpler than error diffusion. An 8 × 8 threshold matrix defines the halftoning pattern. Many different patterns could be used; the best pattern depends on the type of image being printed and on personal taste. To keep the user interface simple, only one pattern is offered: Bayer's dither. This pattern is very good at preserving fine detail. Preservation of detail is especially important when halftoning text that is not being printed at full intensity.

There are 64 cells in the 8 × 8 threshold matrix. Each cell contains an 8-bit threshold. The page is logically tiled with the matrix. Each pixel's 8-bit value is compared with its corresponding position in the matrix. If the pixel's value is greater than the threshold, a dot is fired at that position; otherwise, no dot is fired. This reduces the 8-bit information for the pixel to 1 bit (fire or don't). The process is repeated for all pixels on the page.

In an 8 × 8 area on the page, the number of dots fired can be anywhere from zero to 64. This means a total of 65 (counting none) different amounts of any primary color can be used to fill an area. The original data is 8-bit, representing 256 levels. Because only 65 patterns are used to represent 256 levels, visible contouring may occur when the specified amount of ink gradually varies over a large region of the page.

An example 4 × 4 threshold matrix is shown below. In this case, the pixel values would be scaled between 0 and 16 before halftoning. If a pixel's value were greater than the corresponding threshold matrix entry, that dot would be fired, otherwise it would not be fired.

4 × 4 Threshold Matrix

0	8	2	10
12	4	14	6
3	11	1	9
15	7	13	5

For example, assume a large homogeneous region were being halftoned, and the scaled values in the region were all 8. The resulting pattern of dots fired would be a checkerboard. This is because every other element in the threshold matrix is less than 8.

An obvious feature of the ordered dither is the geometric artifact that is visible when homogeneous regions are halftoned. At 300 dpi, the artifact is small and usually not objectionable. A shortcoming is the inability to represent 256 separate levels. This means a continuously varying gradient will be broken up into bands (or contours) of pixels that all map onto one of the 65 levels.

Scatter. For the scatter halftoning algorithm, a version of the Floyd-Steinberg error diffusion algorithm[1] is used. Unlike ordered dither, error diffusion is not restricted to 65 patterns. A pixel is examined, and if its 8-bit value is greater than 128, a dot is fired. The difference between the specified value and 255 is the error that is produced by putting down a full drop of ink. This error is diffused among four neighboring pixels, reducing their specified values slightly (see Fig. 8). If the original pixel's 8-bit value is less than 128, no ink is fired, and the error is simply the pixel's value. In this case, the distributed error increases the values of the neighboring pixels.

Pixels are processed from from left to right along each raster. Rasters are processed from top to bottom. The error from each pixel is broken up into four parts, which are distributed

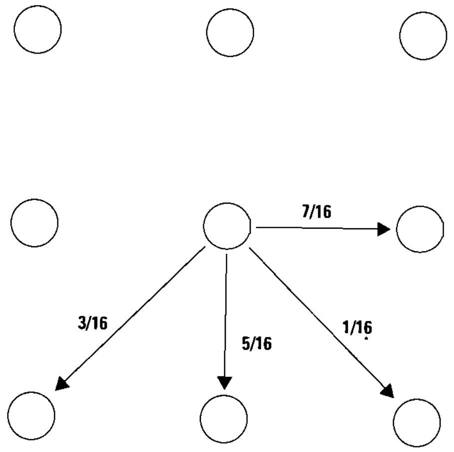


Fig. 8. Error diffusion to neighboring pixels in the scatter halftoning algorithm.

to neighboring pixels. Some noise is added to the error terms to break up artifacts that tend to appear in error diffused data. The average value of the noise is 0, so the image is not lightened or darkened.

Error diffusion does not suffer from contouring. Color gradients are printed as smoothly varying regions of increasing dot density.

Error diffusion can produce artifacts. These are most likely to be visible in large homogeneous regions. It is best suited for complex images like photographs and sophisticated presentation graphics. Hence, it makes a good compliment to the ordered dither algorithm. Error diffusion requires more computation than pattern dither, and can degrade throughput. Pattern dither was chosen as the default halftoning algorithm because it is faster, and is best suited for common types of output.

Grey Balancing

In theory, an equal mixture of cyan, magenta, and yellow inks would produce a neutral (white, grey, or black) color. In practice, this does not occur. The particular inks used by the HP DeskWriter C and DeskJet 500C printers, when mixed in equal proportions, typically produce a color with a slight greenish cast. To compensate for this effect, grey balancing is performed before halftoning.

Grey balancing reduces the amount of cyan used for neutral and near-neutral colors. Decreasing cyan increases the relative amounts of magenta and yellow. Magenta and yellow inks together make red, which is the opponent color of green. One can think of the cyan reduction as an increase in red, which compensates for the greenish cast. Unfortunately, reducing the amount of ink on the page makes the color lighter, so the cyan reduction must be balanced against the loss in darkness. Experimentation showed that a cyan:magenta:yellow ratio of 2:3:3 produces good neutral and black colors over a wide range of papers.

The adjustment is made by first computing the saturation of the color.[2] The following equation yields a value for S between 0 and 1:

$$S = \frac{(\max(c, m, y) - \min(c, m, y))}{\max(c, m, y).}$$

In this equation, c, m, and y represent the amounts of cyan, magenta, and yellow inks, respectively. Larger values of S indicate more saturated colors, while 0 indicates a neutral color.

The amount of cyan ink is adjusted based on S. If S is 0, cyan ink is reduced to two thirds of its original value. If S is 1, cyan is unaffected. Cyan ink is adjusted linearly between 100% and 67% for intermediate values of S.

Intensity Slider

Possibly the greatest challenge in creating a plain paper color printer is delivering high-quality output over a range of environmental conditions (temperature and humidity) and on a range of media, from copier paper to high-quality cotton bond. Two problems occur when fully saturated colors are printed on some types of paper, or at high humidities. Color bleed occurs when adjacent colors run into each other and mix. Ink can even bleed through the paper and appear on the back side. This can occur even if shingling is used. Bronzing occurs when too much ink is laid down on the paper and the dye sits on top of the paper fibers rather than soaking in. This overabundance of ink crystalizes on the surface and the crystals reflect light. This causes a shiny reflective surface that actually gets lighter as more ink is laid down.

As it turns out, when these problems arise, reducing the amount of ink used in printing the colors usually results in higher-quality output. Use too much ink and you get the problems described above; use too little, and the output looks dull and washed out.

Other factors affect the user's perception of quality and color accuracy, such as room lighting, computer display variations, personal taste, and the type of data being printed such as line art versus an image. Rather than attempt to characterize all of these factors, we supply a control that is analogous to the brightness control on a television set. This is called the intensity slider.

The intensity slider is a five-position slider available under the `Options` dialog box described above. It allows the user to control the intensity (saturation) of the colors on the page. This is done by controlling how much ink is used to create any particular color, which affects how saturated the color appears as well as other print quality factors described previously. At the slider's lowest setting, it can reduce the amount of ink used to generate a color by as much as 70%. This reduction is applied to the 24-bit data in the rasterized band just before halftoning. At the slider's highest setting, no reduction in ink volume occurs. The degree to which ink is reduced is a nonlinear function dependent on how much ink was specified in the first place. The percentage reduction is larger for more saturated colors, because these colors are most affected by problems associated with media type and environmental conditions.

Edge Enhancement

One unfortunate side effect of the intensity slider is that colors that would normally be a solid area fill of ink are now created with a dithered pattern of dots. This is even true for black printed with the color cartidge. At the minimum setting, about one third of the maximum posssible volume of ink is used. This may produce the best-quality black for area fills, but the edges of black characters will be rough in appearance and may have color halos.

The driver implements a simple edge enhancement algorithm. If a pixel is black and one or more of its four nearest neighbors (north, south, east, or west) are white, it is considered an edge pixel. Edge pixels are always printed with one drop each of cyan, magenta, and yellow. They are never depleted.

Fig. 9 shows how edges are enhanced.

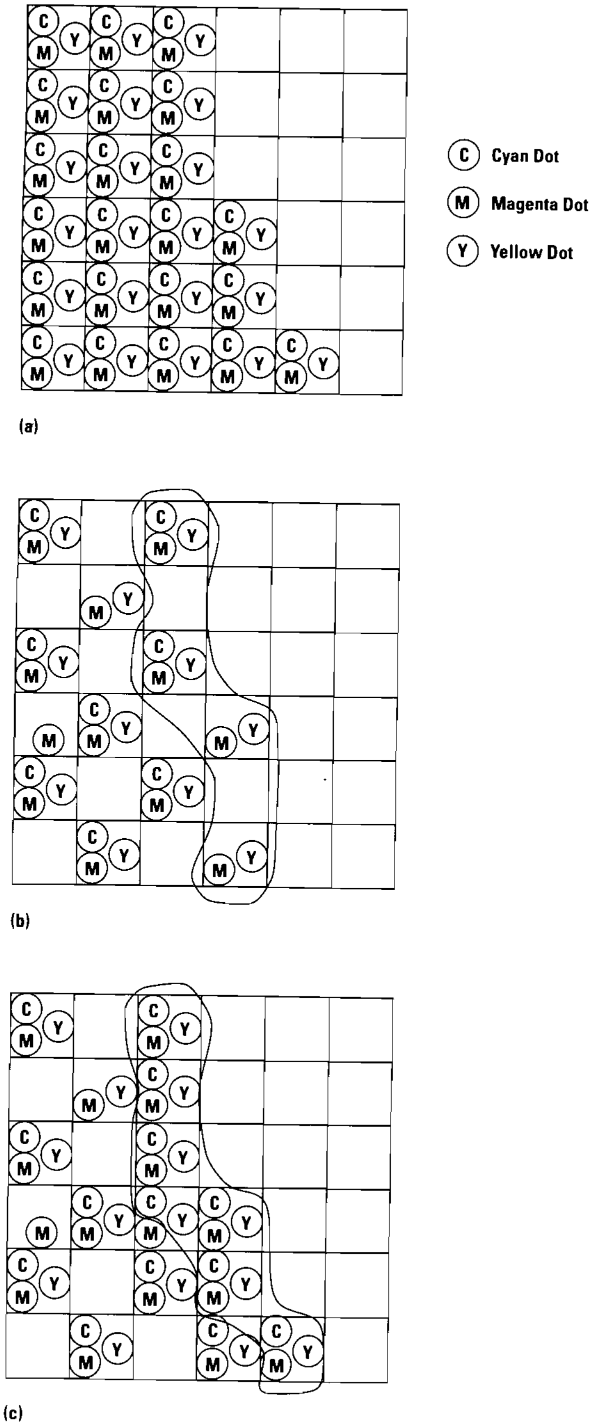


Fig. 9. Edge enhancement in the HP DeskWriter C printer. (a) The edge of a black character with no saturation reduction or color correction. (b) The edge of a black character with color correction and a low setting of the intensity slider. The center of the character will appear black, but the edge is rough because of missing pixels. Also, because unequal amounts of cyan, magenta, and yellow are used to produce black, the edge has a reddish hue or halo because of the absence of cyan dots. If this were the lower right portion of a character, the rightmost pixel of the serif would be totally missing. (c) With edge enhancement, every pixel that is adjacent to a white pixel is printed with cyan, magenta, and yellow dots. This creates a smooth edge without unwanted hues.

Selection of Printed Colors

The color halftoning techniques previously described allow the printer to produce myriad colors. The task of determining which colors to print seems simple, but turns out to be complex. At first glance, one might suggest putting colors on paper that exactly match the colors on the monitor. In practice, this produces surprising results. The situation is further complicated by the type of image printed. Processing a scanned image of a person's face and a bar chart in the same manner may not be a good idea.

The goal is to not surprise users when they receive the output. To this end, the HP DeskWriter C driver allows the user to choose between two color selection paradigms. The default is optimized for simple business graphics, but usually gives acceptable results with any type of output. The Complex Color Printing checkbox biases color selection for scanned photographs, sophisticated presentation graphics, and other complex images.

Chroma-Based Selection (Default). The default color selection model places a high priority on the chroma (colorfulness judged relative to a neutral area of similar lightness) of colors. On CRTs, chroma increases when the beam intensity of one or two of the electron guns is increased. This also produces a lighter color. On paper, chroma is increased by putting down more of one or two primary inks; this darkens the color. In the chroma-based selection scheme, priority is given to chroma over lightness. When printing simple business graphics, such as bar and pie charts, customers usually desire solid, high-chroma colors. The fact that printed colors appear significantly darker than monitor colors is not objectionable; it is usually desirable.

Colors are passed to the driver in RGB format. Red modulates the amount of cyan ink, green modulates magenta ink, and blue controls yellow. More red on the screen means less cyan on the paper. The cyan, magenta, and yellow inks can be thought of as "negative red," "negative blue," and "negative green," respectively.

A one-dimensional correction function is independently applied to each primary before it is halftoned. This function accounts for two factors. First, the perceived intensity of the monitor is not linearly related to electron gun voltage, and second, the perceived darkness on the paper is not linearly related to the amount of ink deposited in a given area.

When high-chroma colors are darkened by the driver, they are not as distinguishable as their counterparts on the monitor. This is not generally a problem, but some applications are capable of producing fairly complex business graphics. For example, in a three-dimensional bar chart, the top, front, and side of a bar can be colored with different tones of the same hue. This gives the illusion of depth on the screen. If the three faces of the bar don't have the correct tones on paper, the sensation of depth is reduced. In this case, appearance-based color selection may give superior results.

Appearance-Based Selection. Scanned photographs and other sophisticated images can be distorted objectionably by chroma-based color selection. In these images, differences in lightness often convey depth information. Artificially darkening high-chroma colors can make the output look unnatural. HP DeskWriter C users can instruct the driver to optimize color selection for these types of output.

A white patch on a monitor is not the same color as white paper. This can easily be seen by holding a piece of paper next to a CRT. White viewed on the monitor will (probably) have a bluish cast. The bluishness is not usually noticeable because the human visual system is remarkably adept at accommodating a wide variety of white points. Through green, grey, and rose colored sunglasses, snow looks white, grass looks green, and other objects appear as expected. This is the phenomenon of color constancy. The visual system adapts to the monitor's white. Only when another suitable reference white is placed in its proximity does the monitor appear bluish.

If colors on paper were selected to match the monitor exactly, monitor white would have to be printed as a pale blue tint. However, the eye has difficulty in accepting tinted paper as white. Because the HP DeskWriter C printer is a 300-dpi binary printer, pale blue must be created by a sparse scattering of relatively large blue dots. Monitor white is homogeneous, while the paper pale blue version would appear textured.

A better approach is to accept the fact that unmarked paper and the monitor appear white when considered independently. Colors are selected for printing so they appear, relative to unmarked paper, the same as the monitor's colors appear relative to the CRT's white point.

Gamut Issues. The gamut of a color device is the set of all colors it can reproduce. Typical monitors have a larger gamut than the HP DeskWriter C printer. This means they can display colors that cannot be reproduced by any combination of the printer's cyan, magenta, and yellow inks. A device's gamut can be modeled as a three-dimensional solid. The shape is irregular, but roughly resembles a lumpy football. The idea is to compress the monitor's gamut so that it fits inside the printer's gamut. Some compromises must be made when choosing a gamut compression algorithm, and although objectionable distortion is controllable, it cannot be eliminated altogether.

Characterize Monitor. To match colors on a monitor, it must be known how the colors on the monitor appear to the viewer. A spectroradiometer can be used to measure the colors produced by various intensities of red, green, and blue on a CRT. The device measures the amount of radiant energy emitted by the monitor as a function of visible wavelength. The system is well-behaved, and a reasonably simple model can be used to predict colors accurately once a few constants have been determined.

Apple's Macintosh color monitors all use Sony Trinitron CRTs. The 13-inch Apple monitor was chosen as the target monitor for the HP DeskWriter C driver. Other sizes of Trinitron CRTs are available from Apple and other vendors. Other brands of CRTs are also available. However, the 13-inch Trinitron heavily dominates our target customer's environment.

Characterize Printer. The HP DeskWriter C printer was characterized by printing a sample consisting of hundreds of small patches of different colors. Each patch contained a known percentage of cyan, magenta, and yellow dots. These were measured with a spectrophotometer. This instrument measures the amount of light reflected at various wavelengths across the visible spectrum. From this data, perceived colors can be calculated.

The HP DeskWriter C and DeskJet 500C printers are designed to be used with HP special paper, HP transparency media, and a wide variety of plain papers. The specified special paper was used to characterize the printer. Transparency color selection is always chroma-based, so rigorous color characterization was not required.

Two sets of samples were created, one using the pattern halftoning technique and one using the scatter technique. Each set was printed on special paper and plain paper, resulting in four sets of samples overall.

The choice of plain paper proved to be very challenging. Good print quality is needed across a wide selection of papers. Patches of eight colors were measured on over sixty varieties of plain paper. With this information in hand, a single "representative" plain paper was selected. This good-quality 25% cotton bond was used for the plain-paper characterization.

The selection of a single target plain paper simplified analysis. The user interface is straightforward; it allows the user a simple three-way selection: plain paper, special paper, or transparency. Although print quality may not be optimized for any given plain paper, it is well-controlled on almost all of them. When color accuracy is critical, HP special paper is recommended.

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and 710 computers. He's now with the HP Measurement and Control Systems Division. Don received his BSEE and MSEE degrees from Colorado State University in 1984 and 1988. He is married and has three children. His interests include fly-fishing, bicycling, skiing, and camping.

64 Color Print Cartridge

Daniel A. Kearl

Dan Kearl is a senior architect at HP's Inkjet Components Division with interests in thin-film and microelectronic process development. He contributed to the DeskJet/DeskWriter color print cartridge architecture and testing. A native of Bellevue, Washington, he graduated from Washington State University in 1980 with a BS degree in physical metallurgical engineering and joined HP's Loveland Technology Center the same year. He has done process development for IC assembly and packaging, for thin-film deposition for both precision resistor networks and inkjet print cartridges, and for thermal inkjet barrier film imaging. He serves on advisory boards for local school and college technology programs, and has a special interest in "antique technology"—steam engines, gas engines, tractors, and hydropower—collecting, restoring, and running the "old iron", and collecting books of the era. His other interests include greenhouse gardening, sailing, old motor boats, and beer and wine making.

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Mike Ard is an R&D project manager at HP's Vancouver Division. He was project manager for development of the firmware and electronics for the DeskJet 500C and DeskWriter C printers. He received his BS and MS degrees in computer science from Brigham Young University in 1975 and 1978 and joined HP's Data Systems Division in 1976, moving to the Vancouver Division three years later. Mike was born in St. Anthony, Idaho. He is married and has seven children. He coaches youth basketball and is involved in church activities.

69 Ink & Cartridge Development

Craig Maze

Craig Maze helped develop the inks for the DeskJet/DeskWriter color print cartridge. With HP since 1978, he has also worked on liquid crystal displays for calculators, IC process development, and print cartridge architecture. He received his BS degree in chemical engineering from Purdue University in 1959 and his PhD in chemical engineering from Iowa State University in 1970. Before coming to HP, he worked on IC packaging and liquid crystal displays for Motorola and on aerospace materials engineering for Martin-Marietta. A member of the American Chemical Society and the American Institute of Chemical Engineers, he is named as an inventor on two patents related to liquid crystal displays.

Loren E. Johnson

An ink chemist at HP's Inkjet Components Division, Loren Johnson helped develop the inks for the DeskJet/DeskWriter color print cartridge. He has also worked on inks for previous DeskJet and ThinkJet products, on etch process development for the ThinkJet printhead, on ThinkJet ink manufacturing, and on evaluation of thermal printer papers. He joined HP at the Vancouver Division in 1981. A native of Rapid City, South Dakota, he received his BS and MS degrees in chemistry from the South Dakota School of Mines and Technology in 1978 and 1980. Six patents on inkjet ink compositions have resulted from his work. Loren is married and has a daughter. His interests include hiking, fishing, computer gaming, xerobotany, drawing, science fiction, pottery, and cross-country skiing.

Daniel A. Kearl

Author's biography appears elsewhere in this section.

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Jay Shields is an R&D chemist at HP's Inkjet Components Division. With HP since 1988, he was on the ink development team for the DeskJet 500C/DeskWriter C color print cartridge. He received his BS degree in chemistry from Bradley University in 1982 and his PhD degree in analytical chemistry from Oregon State University in 1987. Before coming to HP, he was a research chemist at Dow Chemical. He has published several articles in the area of analytical plasma spectroscopy. Jay is married and enjoys woodworking, wine making, and a variety of outdoor sports.

77 Automated Assembly

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Lee Mason is a mechanical engineer at HP's Inkjet Components Division, specializing in design for manufacturability, machine design, and automated assembly. Born in Pittsburgh, Pennsylvania, he received his BS degree in mechanical engineering from the University of California at Davis in 1981 and joined HP's Corvallis Division the same year, serving as an R&D and production engineer for the HP 75C handheld computer. From 1984 to 1987, he designed turnkey robotic assembly systems at Intelledex Inc. After returning to HP, he did tool design and process development for the DeskJet/DeskWriter black and color print cartridges. In 1992 he received an MBA degree from the University of Oregon. Lee is married and has two daughters. Now that his MBA studies are completed, he hopes to have more time for gardening, bicycling, water skiing, and family activities.

Mark C. Huth

Manufacturing development engineer Mark Huth came to HP's Corvallis Division in 1981, shortly after receiving his BSME degree from the Virginia Polytechnic Institute. He has developed automated print cartridge manufacturing processes for the ThinkJet, DeskJet, and PaintJet printers, and did process development and tool design for the DeskJet/DeskWriter color print cartridge. His professional interests include automated manufacturing and machine vision. Mark is married and has two sons. He is a rock climber and shares interests in soccer and sumo wrestling with his sons.

84 Adhesive Technology

Douglas J. Reed

Doug Reed is a manufacturing development engineer at HP's Inkjet Components Division. For the DeskJet/DeskWriter color print cartridge, he worked in R&D on sealing surface development and in manufacturing on the adhesive dispense process and tooling. He also helped develop the adhesive dispense process and did tooling modification for the DeskJet black print cartridge. Doug received his BSME degree from Oregon State University in 1987 and joined HP the same year. He is a member of the ASME and the Society of Manufacturing Engineers. Born in Elmira, New York, he is married, has three children, and is expecting a fourth. He is involved in church leadership and enjoys fly-fishing, reading, and writing.

Terry M. Lambright

Now with HP's Inkjet Components Division, mechanical development engineer Terry Lambright joined the HP IC Business Division in 1984 as an incoming materials engineer, later working on the encapsulation of TAB circuits for HP 20 Series calculators. For the DeskJet/DeskWriter color print cartridge, his responsibilities included liaison with the printer development team, adhesive selection, and TAB circuit design. Before coming to HP he worked for five years in the nuclear industry on materials decontamination and consolidation, and three years in the aerospace industry on the manufacture of titanium tubing. He's the author of a paper on titanium alloy tube fabrication. Born in Galion, Ohio, he attended the University of Arizona, receiving a BS degree in metallurgical engineering in 1974 and an MS in materials science in 1976. He is married, has two children, is involved in church leadership, and holds the rank of captain in the U.S. Air Force Reserve. His interests include marquetry, woodcarving, reading, and working with international students.

87 Machine Vision

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Mike Monroe is a manufacturing development engineer at HP's Inkjet Components Division. A specialist in optical design, machine vision, and control systems, he joined the HP Corvallis Division in 1979. He has served as a production and service engineer for desktop computers and as an electronic tooling engineer for portable computers and handheld calculators, and developed the machine vision systems for DeskJet/DeskWriter color print cartridge production. Before joining HP he worked on the Viking Mars probe at the Jet Propulsion Laboratory (NASA) and on electronic systems for missile launching submarines. He was also associated with a computer design consulting firm. He received his BSE degree in 1971 from the University of California at Los Angeles, specializing in electronics engineering. A member of the IEEE, he was born in Salt Lake City, Utah and served in the Air National Guard for six years, attaining the rank of sergeant. He is married, has two daughters, and enjoys making telescopes, metalworking, and woodworking.

93 DeskWriter C Driver

William J. Allen

Will Allen was one of the developers of the software drivers for the DeskJet 500C and DeskWriter C color inkjet printers. Born in Lafayette, Indiana, he received his BS degree in computer science from Purdue University in 1982. After joining HP in Colorado in 1983, he developed firmware for the HP 16500 and 1630G logic analyzers, then left HP briefly in 1987 to join a startup company in Oregon, where he developed automated test equipment software. Rejoining HP a few months later at the Vancouver Division, he served as a product support engineer, and in 1989 moved to the R&D lab, where he has worked on printer motion control firmware and software drivers. Will is married, has three children, and coaches a youth soccer team. His other interests include travel, bicycling, swimming, table tennis and track work at auto races.

Toni D. Courville

Software development engineer Toni Courville received her BS degree in computer science from Portland State University in 1988. With HP's Vancouver Division since 1988, she has worked on firmware for the DeskJet 500 and DeskWriter printers, and helped develop the driver for the DeskWriter C. She is a native of Boise, Idaho and enjoys bicycling, skiing, and other outdoor activities.

Steven O. Miller

Steven Miller has done software and firmware engineering for HP's Vancouver Division since 1985, contributing to the firmware and driver design of the RuggedWriter, DeskWriter, and DeskWriter C printers. A native of Bellevue, Washington, he received BS degrees in computer engineering and computer science from Oregon State University in 1985. A patent on a data compression scheme names him as an inventor. Steven is married, has two children, and enjoys boardsailing, golf, skiing, and white-water rafting.

103 MRP Action Manager

Alvina Y. Nishimoto

An engineer/scientist at HP's Software Technology Division, Alvina Nishimoto is responsible for the development, enhancement, and support of manufacturing software products. She joined HP in 1978 after receiving both her BS and MS degrees in industrial engineering from Stanford University that same year. Her professional interests include software reuse and software development processes. Alvina was born in Honolulu, Hawaii.

William J. Gray

A development engineer on the HP MRP Action Manager project at HP's Manufacturing Productivity Division (MPD), Bill Gray is currently a development engineer at HP's Professional Services Division. He joined MPD in 1983 after receiving a BS in computer science from North Carolina State University that same year. Bill was born in Macon, Georgia, is married, and has one child. His recreational activities include golf, bowling, soccer, and racquetball.

Barbara J. Williams

Currently a software manufacturing engineering manager at HP's Scientific Instruments Division, Barbara Williams was the project manager for the HP MRP Action Manager project at HP's Manufacturing Productivity Division. Barb joined HP's Computer Systems Division in 1982. She worked as a development engineer on the HP PM/3000 and HP MM/3000 products and as a project manager for the A.02.00 release of the HP Purchasing enhancements project. While attending college she worked as a software engineer in a summer intern program at Bell Laboratories. She has a BS degree (1982) in computer science from Washington State University and she is certified in production and inventory management (CPIM) by the American Production and Inventory Control Society. Managing people, processes, and projects are her main professional interests. She served as a United Way loaned executive for HP in 1991. Born in Wenatchee, Washington, she is married and expects her first child in the summer. Sewing, aerobics, swimming, tennis, camping, waterskiing, gardening, and volleyball are among her recreational activities.