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High-Quality Color Inkjet Office Printers

The HP DeskJet 1200C and 1200C/PS printers are a new class of HP DeskJet printers for office applications. They offer black and color printing, fast print speeds, scalable typefaces, expandable memory, networking options, PCL 5 and PostScript™ languages, and HP LaserJet printer compatibility.

by Douglas R. Watson and Hatem E. Mostafa

When HP introduced the PaintJet¹ and DeskJet² printers in 1987 and 1988, customer expectations of personal printers were changed. Customers learned to expect quiet operation, exceptional color, and low cost with good throughput in an affordable personal printer.

Together, these two printers provided a full-featured printing solution. However, each printer had limitations that kept it from being the single desktop product for all printing needs. The DeskJet delivered high-quality plain paper text with industry-leading speed in an affordable printer, but there were still opportunities to improve print quality when printing on a variety of papers including the newly appearing recycled papers. The PaintJet delivered high-quality color at a low price but lacked plain paper capability and the 300-dpi text that the HP LaserJet printer family had made a minimum requirement for general-purpose office printers. The DeskJet 500C printer³ introduced in August 1991 added plain paper color capability to the product line. The DeskJet 500C and the two-pen DeskJet 550C continued the march of inkjet technology toward the mainstream office.

In May 1992, the HP PaintJet XL300 printer delivered the first true laser-quality color capability for the mainstream office. This product offered exceptional print quality. Its price and size positioned it as a superior shared or networked solution.

After assessing customer needs, product development teams were formed for the new HP DeskJet 1200C printer and several new print cartridges. The objective was to deliver a high-performance personal and office printer combining all of the best features of the existing products while extending the technology in the areas of throughput, quality, and cost. During the development cycle the opportunity to apply the print cartridges under development to the large-format market became apparent. A team was formed to adapt the cartridges to the DesignJet 650C large-format drafting plotter to meet those needs. The R&D teams accepted the challenge of incorporating all of these goals in one program, delivering the benefits of this new technology in two products with seven new but highly leveraged print cartridges.

Customer-Driven Development

The design objectives for the DeskJet 1200C were set with the overriding goal of moving color into the mainstream office market using inkjet technology without sacrificing the

features to which customers had become accustomed in laser printers. This resulted in the following specific objectives:

- Laser-speed text printing—more than four pages per minute (seven pages per minute was ultimately achieved, and six is specified)
- Industry-leading color quality on plain paper
- Fast color throughput—one to two minutes per page
- Color cost per copy better than any technology at any use rate
- Desktop form factor—less than 20 inches wide
- Improved transparency and glossy paper performance
- Product cost less than or equal to laser printers of equivalent capability
- Ink supply sensing for network or batch print jobs.

In addition to being asked to deliver the first truly mainstream color printer for the office, the DeskJet 1200C and print cartridge program team was also charged with delivering the solution to the marketplace in less than two years, a record time for such an advanced product/print cartridge system. To meet this aggressive time-to-market goal, the printer and print cartridge teams had to make fundamental changes in the processes by which such print systems are developed.

To translate the list of objectives into designs, teams were formed to choose the best implementation solutions without regard to whether a particular solution was implemented in the product, print cartridge, or media. These teams, called *seam teams*, were composed entirely of and led by engineers. At an extraordinary rate, they developed technical solutions to the objectives that offered the highest quality and the lowest cost. The result is a well-tuned high-performance printer that delivers all of the major desires identified by customers.

On the printer development team, the traditional roles of design, manufacturing, and reliability engineering were all combined into a single role: that of the development engineer. The development engineers became solely responsible for the design, manufacturability, assemblability, testability, and reliability of their parts. This structure greatly empowered the engineering team and allowed rapid, global optimization of major design and architectural decisions. New rapid prototyping techniques were developed to improve both the accuracy and the timeliness of early prototype



Fig. 1. The HP DeskJet 1200C and 1200C/PS printers are 600-by-300-dpi black and color inkjet printers for office applications.

units. In addition, new aggressive tooling strategies shaved months from the traditional tooling cycle times. Finally, early supplier involvement, including early interaction of HP production people with all the design aspects of the product ensured rapid convergence of all manufacturing issues. As a result of this streamlined development process, the laboratory phase of the development cycle for the HP DeskJet 1200C printer was completed in the shortest time in the division's history.

The other DeskJet 1200C articles in this issue describe in greater detail the design solutions arrived at by the seam teams. The remainder of this article describes the features and capabilities of the HP DeskJet 1200C printer and the HP DeskJet 1200C/PS PostScript printer.

DeskJet 1200C Features

The DeskJet 1200C and 1200C/PS printers (Fig. 1) are the most advanced HP DeskJet printers, building on the features of earlier DeskJet printers and adding features that are new to the family.

Using a new family of inkjet print cartridges, the new printers print black text with a resolution of 600 by 300 dots per inch (dpi) and HP Resolution Enhancement technology (Fig. 2). Print speeds are six pages per minute for black text and one to two minutes per page for color (Fig. 3). The design duty cycle is 8,000 pages per month.

The new printers raise inkjet technology to a new level of print quality, producing sharp, black text and a spectrum of colors on plain paper using four new 104-nozzle print cartridges—cyan, magenta, yellow, and black—with new ink formulations. To ensure the blackest, sharpest text and maximum graphics quality, the black cartridge contains pigmented ink. The cartridges have large-capacity ink reservoirs and ink-level indicators.

The DeskJet 1200C memory is 2M bytes, expandable to 26M bytes, and the DeskJet 1200C/PS memory is 4M bytes, expandable to 20M bytes. The expansion memory comes from the same SIMM products used in the HP LaserJet 4 and 4Si printers and is available in increments of 1M, 2M, 4M, and 8M bytes.



1234 Main Street, Anytown, CO 88822

May 3, 1993

John Adams
Acme Consolidated
1100 J Street
Anyville, IL 11133

John:

I just came across a product that fits right in with our conversation at lunch last week. Remember when you told me how impressive your competition's presentation looked, with full-color overheads and color charts in the proposal? Well, I have the answer for you.

Ruth Jones, our always-a-step-ahead PC coordinator, clued me in on Hewlett-Packard's DeskJet 1200C printer. This one's really worth checking out, John. Even though it prints dynamite color, the HP DeskJet 1200C is an all-around office printer that thinks like your HP LaserJet—no fooling. It uses the same printer language, typefaces, print margins—you can even use the same LaserJet accessories! (Yes, including those HP JetDirect cards you're using for easy networking.)

About that color—it's worth the price all by itself. The DeskJet 1200C prints out the rich, professional-looking color you've been dreaming about for months—the kind your competitors would love to have. Ruth tells me this printer can do millions of colors, just the thing for that new color monitor of yours.

So how do I know this is such a swell product? Simple—after seeing a DeskJet 1200C in action, I knew this was the printer for us. Did I mention that it's from Hewlett-Packard? It was an easy decision, believe me. I know you've been wanting to bring color into your office. Somehow, I have the feeling that the DeskJet 1200C is the printer you've been waiting for. Let me know if you want more info.

On the run (as usual),

Jim Smith
Information Systems Manager

Fig. 2. Black text is printed at six pages per minute in fast mode and four pages per minute in high-quality mode.

★ Using Color in the Office

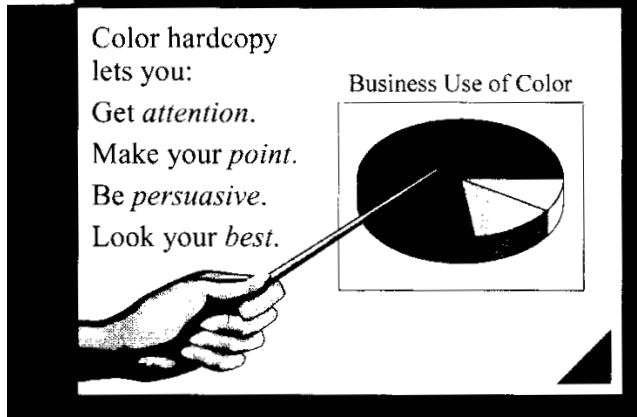


Fig. 3. Color printing takes one to two minutes per page.

A PostScript Level 2 Module is available to add PostScript language capability to the DeskJet 1200C printer. The module provides the same PostScript Level 2 functions as the DeskJet 1200C/PS printer. Both the DeskJet 1200C/PS and the DeskJet 1200C with the PostScript module provide auto-switching between interfaces and between the PCL 5 and PostScript languages.

Drivers for the new printers are available for Microsoft® Windows and Apple Macintosh environments.

LaserJet Printer Compatibility

The new printers are the first DeskJet printers that are HP LaserJet compatible. The DeskJet 1200C shares with the LaserJet 4 such features as:

- Color PCL 5 language including the HP-GL 2 graphics language
- 45 internal scalable typefaces—35 Intellifont and 10 TrueType™
- HP Resolution Enhancement technology
- Interchangeable scalable and bitmapped typeface cartridges
- Interchangeable SIMM memory and HP JetDirect cards that are also compatible with the HP LaserJet IIISi printer
- RISC-based processing
- High-speed Centronics parallel port
- Automatic switching between Centronics and network interfaces through optional HP JetDirect cards
- Automatic switching between PCL 5 and optional PostScript language
- Support for explicit language switching as found on the LaserJet IIISi printer.

Acknowledgments

We wish to acknowledge the engineers, scientists and managers who throughout this program dedicated themselves to delivering to HP customers the highest value possible. Through their efforts traditional technical and performance barriers fell rapidly, making possible a new class of DeskJet printer for the office.

References

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3. *Hewlett-Packard Journal*, Vol. 43, no. 4, August 1992, pp. 64-102.

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TrueType is a U.S. trademark of Apple Computer, Inc.

Laser-Comparable Inkjet Text Printing

The HP DeskJet 1200C printer achieves laser quality by means of pigmented black ink and precise, mode dependent control of drop volume. Contributing to laser printing speed are an intelligent print mode forecaster, a large memory capacity, heated drying, improved media handling, a larger printhead, and a high firing rate made possible by careful attention to refill dynamics.

by **Jaime H. Bohórquez, Brian P. Canfield, Kenneth J. Courian, Frank Drogo, Corrina A.E. Hall, Clayton L. Holstun, Aneesa R. Scandalis, and Michele E. Shepard**

The mission of the HP Deskjet 1200C print cartridge and product development team was to deliver text quality and speed that meets the expectations of the office printer market. The office standard for text printing has been set by the HP LaserJet series of printers. To be a general-purpose office printer, a printer must provide text quality, output speed and connectivity comparable to LaserJet printers, along with LaserJet language compatibility. This article discusses how two of those objectives—text quality and speed—were achieved. The article on page NO TAG discusses the compatibility and connectivity solutions.

Text Quality Fundamentals

Several attributes define the text quality of a printed page, regardless of whether its source is a serial impact dot matrix printer, a thermal inkjet printer, a laser printer, or a printing press. The fundamental characteristics that define print quality are:

- Character hue and darkness
- Edge smoothness or roughness
- Character edge contrast
- Presence of artifacts
- Uniformity of area fills.

Character darkness, or optical density, is a measure of the blackness (lack of lightness) of the printed image. In general, most surveys indicate that customers prefer darker characters over lighter characters. Hue refers to the tone of the color used to print the character. Even black characters can be slightly cold (bluish) or warm (brownish). The ability of the eye to distinguish small differences in hue diminishes at high optical densities.

In text printing, edge roughness is determined by several factors including printer resolution (often measured in dots per inch), dot placement accuracy, rendering algorithms, and the interactions between the colorant (e.g., the laser toner or the inkjet ink) and the paper. In general, higher resolutions produce smoother edges because they allow smaller changes in dot placement and the individual picture elements (pixels) correspond to smaller areas. Fig. 1 illustrates the improvement obtained by increasing resolution from 150 to 300 dpi with a binary printer. Firmware and hardware-based algorithms can be used to enhance edge smoothness further by judiciously placing dots between the basic grid points or by changing the dot size.

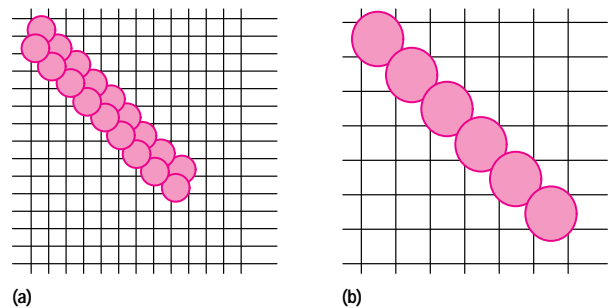


Fig. 1. Comparison of edge smoothness at two resolutions. (a) Line drawn at 300 dpi resolution. (b) Line drawn at 150 dpi resolution.

The contrast between the printed character and the background paper is affected by the optical density of the ink and toner, the color and brightness of the paper, and the edge transition sharpness of the printed area. For high-quality, high-contrast printing, the dark printed zones must transition sharply into unprinted zones. If the printed area slowly fades into unprinted paper, the characters appear fuzzy and soft.

Unwanted artifacts, such as inkjet spray and laser background scatter, can also make characters appear fuzzy. Inkjet spray is the presence of small, unwanted dots near the printed zones. In laser printing a similar phenomenon, called scatter, sometimes occurs, leaving undesirable toner particles near the printed zones.

Solid area fills, used for graphics and large font rendition, should be uniform and dark. Nonuniformity of area fills can occur in a variety of ways, such as the mottle (light and dark areas) caused by the uneven penetration of an inkjet ink, the uneven gloss seen on many laser prints, banding, and density gradients.

Text Speed

Typical inkjet printers have text throughput ratings of one to three pages per minute. Laser print engines deliver four pages per minute in their low-end designs, 8 to 10 pages per minute in the midrange designs, and as much as 16 to 20 pages per minute in the relatively expensive shared network devices. Our market target matched the low-end to mid-range lasers, so we made our minimum throughput goal for

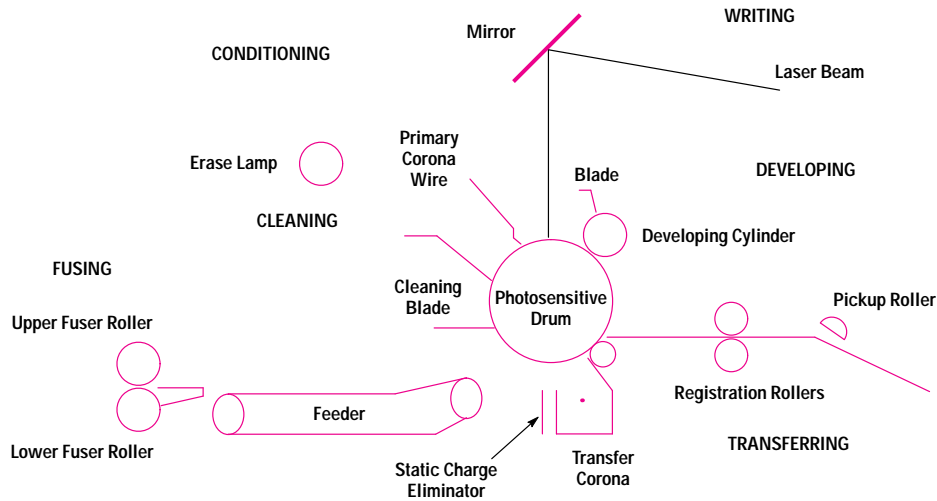


Fig. 2. HP LaserJet IIIIP electrophotographic print engine.

high-quality text a true four pages per minute as measured by industry analysts' latest printer text benchmarks.

Comparing the Technologies

HP LaserJet printers and HP thermal inkjet printers use significantly different printing technologies. Each process has inherent advantages and engineering challenges. Fig. 2 illustrates the electrophotographic printing process and Fig. 3 shows the inkjet drop generation process. The basics of the thermal inkjet printing engine are described in "An Inside View of the Drop Generation Process" on page 11.

Laser printing has several high-value attributes. It provides a high degree of media independence, it is a high-speed page printing process, it is a dry process that doesn't wet the paper so physical distortions of the media are minimized, and it produces durable print unaffected by water and highlighters. Excellent character edge smoothness is achieved by the fusing process and the small toner particle size. Dot size can be adjusted, and customers perceive the process to be highly reliable.

Thermal inkjet printing also has attributes that have been engineered to deliver customer value. It uses a low-cost print engine (the disposable inkjet cartridge). Printer mechanism simplicity is possible for low-end designs. It can do single-pass full-color printing and has fewer limitations in producing

graphic area fills. The requirements for producing good inkjet text quality and speed can be summarized as follows:

- Pick a high resolution (300 dpi minimum)
- Eject uniform drops of the correct size, shape, and velocity at a high frequency
- Place the dots precisely on the paper
- Control the ink-media interaction
- Make the printer mechanism fast and intelligent.

The rest of this article will describe how the design teams achieved these goals during the Deskjet 1200C printer and black ink cartridge development.

Controlling Drop Size and Shape

To provide text and images that are as sharp and crisp as laser output, the size, shape, and consistency of the drops must be controlled. Since the drops are the result of a nucleated bubble, nucleation must be repeatable from firing to firing. One way to ensure this is to use very narrow heating pulse widths. By transferring energy to a thin layer of ink over the heating resistor rapidly, defects on the resistor surface that trap gas do not have a chance to alter the nucleation, so each drop looks like the others.¹

The print cartridge also needs to be fired very fast (8 kHz) so that the printer will have laser-comparable throughput. It is easy to make a print cartridge refill this fast, but the trick

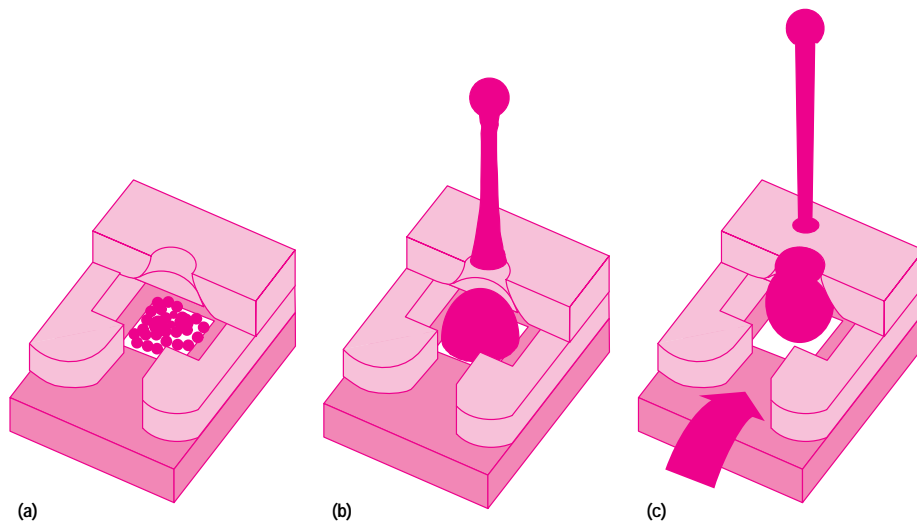


Fig. 3. Inkjet print engine drop ejection process. (a) Nucleation. (b) Bubble growth and drop ejection. (c) Refill.

An Inside View of the Drop Generation Process

The bulk of the print cartridge for the HP DeskJet 1200C printer is a reservoir—a flexible bag—of ink that is connected to the printhead through a passage called the snout. In the printhead there are many small holes, or orifices, through which ink flows to generate the dots on the paper. Unlike most containers that have a set of holes in the bottom, this one will not leak. The ink is held up by a spring in the bag which exerts a force outward on the walls of the bag producing a backpressure that prevents the ink from drooling. The ink would be pulled up into the main reservoir away from the printhead if it were not for opposing capillary forces from the exit orifices, which pull back on the ink, holding it in static equilibrium.

Imagine yourself inside one of the drop generators that exists above each exit orifice. Below you is the hole, which does not drool, thanks to the gentle balance of spring-bag and capillary forces. You are surrounded by a square chamber that has a refill channel cut into one wall, providing access to the reservoir of ink and restricting the flow enough to stabilize the refill process. The ceiling is covered by a flat, square, thin-film resistor, which is connected through an electrical circuit to power circuitry in the printer.

The drop ejection process is shown in Fig. 3 on page 10. It begins suddenly as the ceiling heats up hundreds of degrees Celsius per microsecond. Because the temperature rise is so fast, only a very thin layer of the ink that is in contact with the resistor heats up with it. As that fluid reaches its boiling temperature any small air bubble trapped on the surface will start to grow. However, around the bubble the ink is still heating. When it reaches its superheat temperature limit, the ink can no longer exist in the liquid state because of thermodynamic instability. The ink rapidly vaporizes, creating a pressure wave that acts like a piston to fire the slug of ink in the chamber (with you entrained within it) out of the chamber and through the exit orifice. As the ink slug leaves, air rushes in around it, filling the space that had been occupied by the ink. The air rushes around the ink droplet as the tail breaks off and the ink remaining in the chamber reforms to produce a meniscus, or an air-to-ink interface, which connects by surface tension to the smooth inner walls of the exit orifice.

The meniscus shape is distorted by many factors: the shape of the vaporized ink piston, the state of the fluid's velocity field immediately before vaporization, and the imbalances in the wetting of the exit orifice by the ink. However confused this surface may be, the capillary forces still dominate the force balance, causing the

meniscus to climb up the exit orifice, drawing a new charge of ink into the chamber behind it. That charge is pulled against the resistance of the spring bag and the choked refill channel. The inertia of this charge causes the ink to bulge out the exit orifice, which starts to pull back on the overshooting meniscus as soon as it passes the exit plane. Eventually the ink flow is reversed by this force, causing the bulge of ink to return to the drop generation chamber. Over a few cycles this bouncing meniscus damps out and returns to equilibrium. The system is intentionally under-damped to increase the speed with which the ink first crosses the equilibrium plane.

The point at which a new firing cycle is initiated in this refill process has a lot to do with the shape and consistency of the droplets produced (see Fig. 1). If the next firing is well after the meniscus bouncing damps out, the next droplet will be as well-formed as the first. Unfortunately, the repetition frequency that can be achieved in this way is usually too slow to meet the print speed goals. If firing is attempted before the first meniscus equilibrium crossing, then the drops will be fast and spear-shaped, leading to poor print quality. If the next firing occurs near the largest excursion of the refill charge outside of the orifice, the drops will be slow and dumbbell-shaped, again leading to poor print quality. Between these two points well-formed drops can be produced that do produce optimum print quality. This is the earliest point in the refill process that well-formed drops can be produced.

While the new charge is being prepared for the next shot, the last drop travels across the printhead-to-media gap and hits the media. If the drop is well-formed, both the head and the tail of the drop will hit the media in the same spot. On the media a new set of processes take over. The media must first begin to wet, overcoming its resistance to penetration of the ink into it. This happens quickly with HP inks, and the processes of ink penetrating into the media, of ink wicking along fibers on the surface of the media, and of the ink's volatile components evaporating off begin in parallel. The rate at which each of these processes happens relative to the others affects the print quality. More detail on these processes can be obtained from the accompanying article and the article on page NO TAG.

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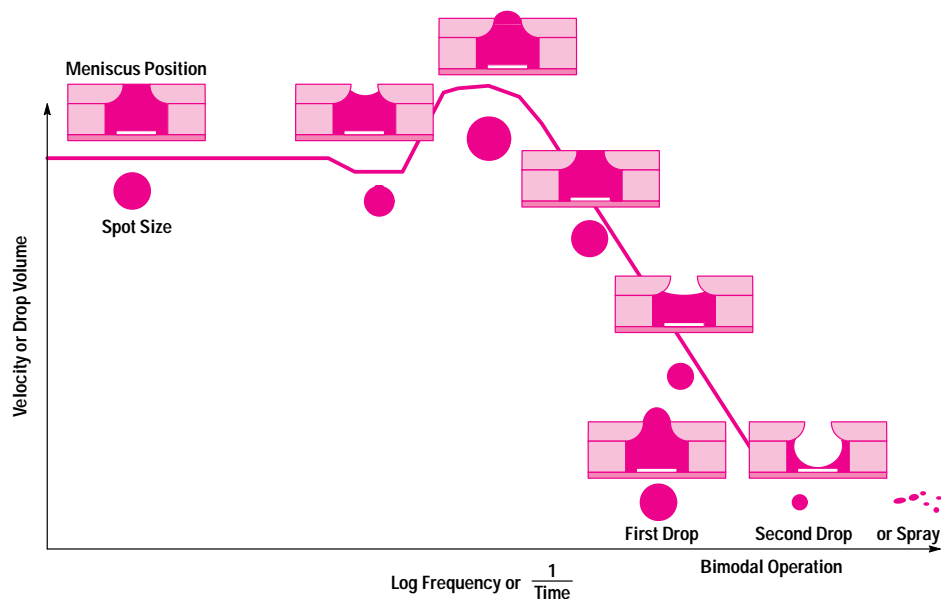


Fig. 1. Meniscus dynamics and drop volume as a function of drop frequency.

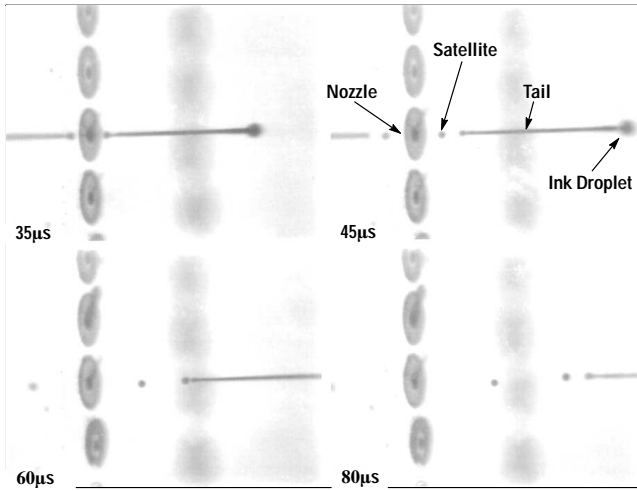


Fig. 4. Tail of ink droplet with satellites at different times after drop ejection.

is to do it and not have the ink rush in with such momentum that it overflows the orifice and spills out onto the top plate. This effect, called puddling, will pull the following drops in the direction of the puddle. This results in the drop landing off-target, and can cause it to break up into spray drops. The dimensions of the pipe refilling the chamber are adjusted to achieve the right balance between refill speed and fluidic damping. Drops can also land off-target if all of the parts of the system (resistor, barrier, and orifice) are not well-aligned.

One characteristic of the pigmented ink used in the DeskJet 1200C black print cartridge is that the tail of the drop tends to stay together much longer than with the dye-based inks used in previous HP inkjet print cartridges. This is an advantage in that it does not break up into random, uncontrollable spray droplets. It is also a disadvantage because anything that disturbs the symmetric nature of the tail may cause it to form one or two large, consistent spray droplets we call satellites (see Fig. 4).

Another fundamental quantity necessary for print cartridge development and tuning is the size of the drop, or the drop volume. There is a design volume, which is defined as the drop volume that a print cartridge design would produce under controlled conditions in a drop volume tester. Testing conditions are kept constant and repeated for all print cartridges so that comparisons can be made. However, the realities of a user plot can vary from that of the laboratory model. For instance, the printhead temperature will vary with the density of drops being fired, and this in turn affects the drop volume. Therefore, the *system drop volume* was conceived as a more meaningful measure of drop size. It correlates with the drop volume expected under actual printer conditions and is determined as follows.

Since the print cartridge is a manufactured product made in large quantities, the randomness of nature ensures that the drop volume will vary by some amount from print cartridge to print cartridge. This variation must be constrained within a certain range for the customer to get consistent results in all environmental conditions, on different media, and using different print modes. A lower drop volume limit is defined by user approval of, among other things, light areas in text, and an upper limit is defined by excessive color bleed on

transparency film in high humidity. To determine the system drop volume limits, print cartridges were operated at a number of different setpoints, using all of the printer's print modes (high-quality, normal, fast). A wide selection of media were used including those with low dot gain such as bond papers, glossy paper, and transparency film, and those with high dot gain such as HP CX JetSeries paper. The printing was done in a range of environmental conditions with both text and graphics files. A panel of users picked the minimum and maximum acceptable system drop volumes.

Drop Volume Distribution

Once the acceptable drop volume range has been determined, all the factors that contribute to the production of that drop can be analyzed to ensure that all the print cartridges that are manufactured always produce drop volumes that fall inside the range. The drop volume distribution is composed of print cartridge manufacturing variations, environmental variables, and changes caused by the print cartridge itself.

The manufacturing variations include obvious factors such as the size of the orifice and the size of the resistor, both of which will vary within the specified tolerance limits. Drop volume can also be affected by other, more subtle variations. Among these is the change in drop volume resulting from a change in the frequency response of the print cartridge caused by variations in the size of the refill channel.

Environmental factors encompass everything external to the print cartridge. Printer-supplied energy, ambient temperature, and the temperature inside the printer all can conspire to change the print cartridge's drop volume.

The print cartridge itself adds the largest contributions to the budget. As ink is used, the print cartridge's back pressure will trend upward, which will reduce drop volume. Repeated firings can alter the resistor's surface which in turn can effect the delivered volume. The largest contribution by far is the increase in drop volume as the temperature of the printhead rises during drop firing—an effect called thermal inkjet heating.

A Monte Carlo analysis of all of these factors yields a distribution of expected drop volumes (Fig. 5). The low end of the range was set high enough to fill dark areas completely. Then, when the high end of the range exceeded the allowable limit, each of the factors was examined to find a way to reduce the budget. Tightening manufacturing tolerances produced small budget reductions, but had very large cost consequences. The environment was deemed to be out of

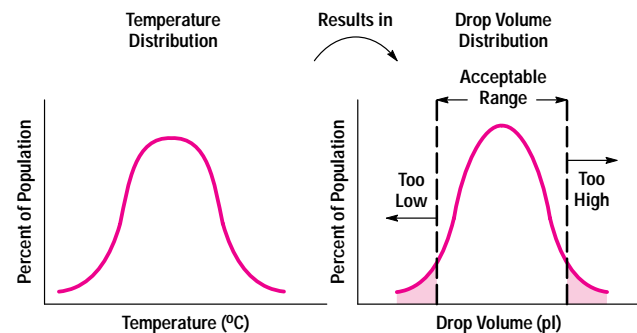


Fig. 5. Printhead temperature is the largest contributor to inkjet drop volume variations.

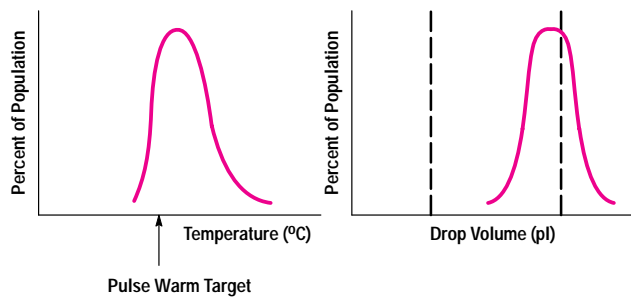


Fig. 6. Prewarming the printhead before printing truncates the temperature distribution and shifts and narrows the drop volume distribution.

the print cartridge's control. However, controlling the printhead temperature through the use of thermal inkjet heating proved feasible.

With all of the built-in heaters in the form of firing resistors, the printhead has plenty of warming capacity. A scheme of having the printer send energy pulses to the print cartridge to warm up the printhead to some initial temperature before printing was devised. The pulses have enough energy to warm the printhead, but not enough to fire a drop of ink. By warming every print cartridge to a given temperature above ambient before printing, the lower portion of the temperature distribution input is effectively truncated, and thus the drop volume distribution is shifted (Fig. 6). The higher the initial temperature to which the printhead is warmed, the smaller is the contribution of the temperature to the drop volume budget. Because the volume distribution is narrowed, the nominal value of the drop volume can be lowered while still keeping the tails of the distribution within the desired limits (Fig. 7).

The drop volume was selected primarily so that text and figures would always be completely closed (with no white space showing) when two drops are printed in 600-by-300-dpi pixel locations. The printer also has a faster printing mode in which the carriage is scanned twice as fast, but the printer only puts down one drop in each 300-dpi pixel location. The ability to warm the print cartridge to differing temperatures before to printing allowed the drop volume to be customized for each print mode, thereby putting down just the right amount of ink to get the job done. By setting a higher warming temperature for the fast mode, a larger drop is produced that more nearly fills in all of the space.

Black Ink Design for Media Independence

Once the print cartridge and printer mechanism have done their job and delivered a well-formed, well-placed drop of

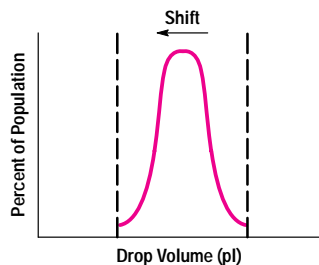


Fig. 7. Lowering the nominal drop volume shifts the narrowed drop volume distribution downward so that it falls within the limits.

ink on the paper, it's up to the ink to set the proper image on the paper. Bares² has described many of the physiochemical differences in office papers and some of the ink design issues caused by these differences, such as achieving uniform optical density and dot shape.

The ink is responsible for the printed image's optical density. In the past, poor ink-media interactions have produced print quality that did not match laser quality on many types of commonly available office papers because of low optical density and feathering (wicking along paper fibers). One of the ink development chemists' primary design goals for the DeskJet 1200C was to produce a black ink that gives uniformly good performance over as many office papers as possible. This translates to an ink that maintains optical density and uniform dot size on all paper types and does not feather or wick.

The DeskJet 1200C black ink vehicle is designed to yield excellent text quality. To provide good text edge acuity and high optical density, the ink is constructed so that a drop of ink landing on the substrate medium maintains a hemispherical geometry until the vehicle has been absorbed into the medium. The ink is a pigmented type, which gives better edge acuity than dye-based inks. To further reduce feathering or wicking of the ink along paper fibers, the vehicle formulation was refined until the goal was met.

In general, text print quality is improved with the residence time of the hemispherical drop on the substrate. Although it is tempting to increase drop residence time for improved print quality, any increase necessarily increases the ink drying time and therefore decreases printing throughput. A reasonable compromise between text print quality and drying time was achieved by balancing vehicle components. A combination of several polymers and other solvents is used to improve drop firing reproducibility, increase drop residence time, and decrease ink drying time. An additional solvent further improves print cartridge nozzle crusting characteristics.

The wicking of ink dots is determined in a very short period of time, from less than ten to several hundred milliseconds, during the initial stages of penetration. Even in printers with heaters to improve drying time and cockle, feathering is determined primarily by the ink chemistry and physics during this crucial time period. The tendency of ink to penetrate unevenly along fibers or into capillaries produces misshapen characters. The photographs in Fig. 8 illustrate how well the DeskJet 1200C black ink has been able to improve this.

Pigment Dispersion

Pigment dispersions have been extensively used in the paint and commercial printing industries for the lightfast and waterfast qualities they impart to the final coating. In contrast to the use of dye colorants, which are completely dissolved in the ink vehicle resulting in a true solution, the use of pigments requires the dispersion of solid particles of colorant. It is this solid colorant that gives the resulting coating its light fastness; a sacrificial outer layer of colorant protects the remaining core from deterioration by light and oxidants present in the air surrounding the coating.

The incorporation of solid particles in an inkjet ink poses a tremendous challenge in achieving a dispersion stability sufficient to guarantee that settling or separation of pigment

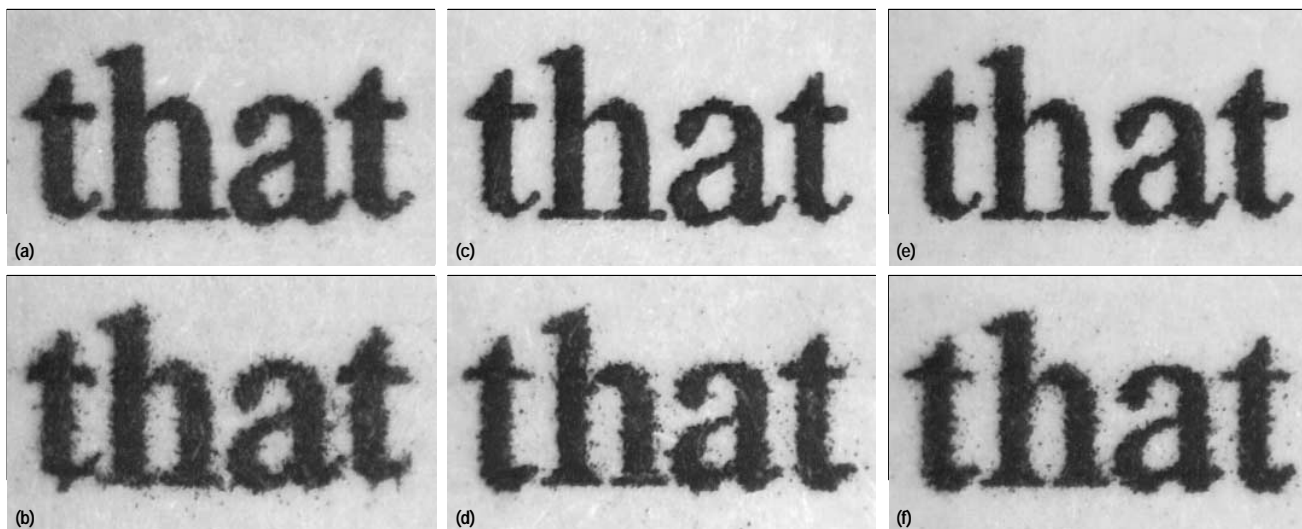


Fig. 8. Photomicrographs showing relative feathering of HP DeskJet 500 and DeskJet 1200C on three papers. (a) DeskJet 1200C on paper A. (b) DeskJet 500 on paper A. (c) DeskJet 1200C on paper B. (d) DeskJet 500 on paper B. (e) DeskJet 1200C on paper C. (f) DeskJet 500 on paper C.

does not occur during a possible print cartridge shelf life of up to two years or upon exposure of the ink to the brutalities of a firing resistor in the interior of the inkjet print cartridge. The stability of the solid colorant particles depends on the ability of the dispersant to adhere to the surface of the pigment, to extend itself into the volume of ink vehicle, and to provide a repulsive environment when the particle is approached by another particle coated with dispersant. Although the exact morphology of a dispersed pigment particle has not been elucidated, the system may be envisioned as a "fuzzy tennis ball," as shown in Fig. 9.

Pigment Selection

Black pigments were initially screened on the basis of the resulting print optical density. In general, "high-jetness" black pigments are all carbon blacks, obtained from the

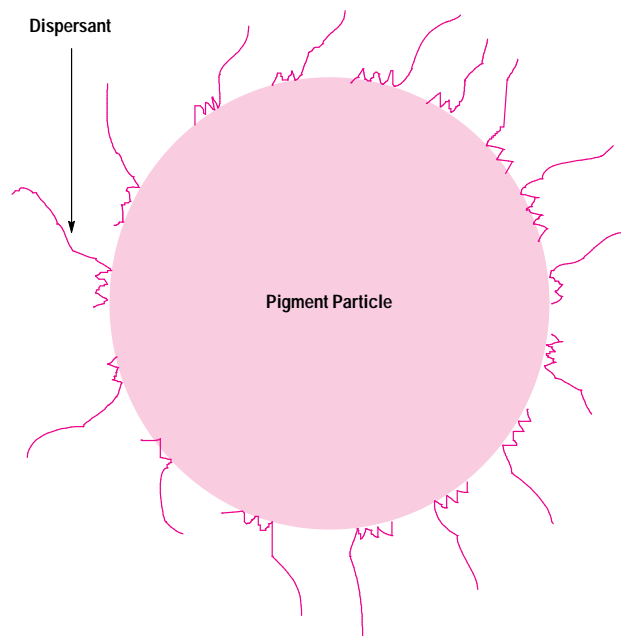


Fig. 9. Dispersed pigment particle.

combustion of organic fuels. Three types of processes are used to produce carbon blacks, resulting in two ranges of primary particle sizes. The highest-jetness pigments were chosen for formulation studies.

Once pigment candidates had been identified that yielded high optical density, a screen of surface treatments was pursued. The pigment was selected on the basis of its ability to form a stable dispersion and on its inertness with respect to corrosion of the print cartridge orifice plate, composed of gold-plated nickel. Table I illustrates the uniformity of optical density we have been able to achieve over a range of papers relative to other printer platforms.

Table I
Optical Density Measurements on a Range of Papers

| Paper | A | B | C | D | E | F | G | H |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| HP Deskjet 500 | 1.1 | 1.3 | 1.3 | 1.3 | 1.2 | 1.3 | 1.1 | 1.3 |
| HP Deskjet 1200C | 1.4 | 1.4 | 1.3 | 1.3 | 1.3 | 1.4 | 1.3 | 1.3 |
| HP LaserJet III | 1.4 | 1.5 | 1.4 | 1.4 | 1.5 | 1.4 | 1.4 | 1.5 |

More uniform optical density, tighter dot size control, less feathering, and better edge acuity have combined to make the HP DeskJet 1200C the most paper independent liquid inkjet printer to date. Fig. 10 demonstrates the relative media independence of the HP Deskjet 500, HP Deskjet 1200C, and HP LaserJet IIP printers on a series of papers selected to represent office papers commonly available worldwide.

Laser-Comparable Printing Speed

The speed of any printer is limited by the rate at which the print job is prepared for printing and by the rate at which the print engine can execute the printing operation. The Deskjet 1200C comes with 2M bytes of RAM to speed the download time from the host computer. Its print mode forecaster interprets raster data from either the PCL 5 or the PostScript™ formatter for the print engine in ways that allow the print engine to maximize the throughput while maintaining the high print quality that customers desire.

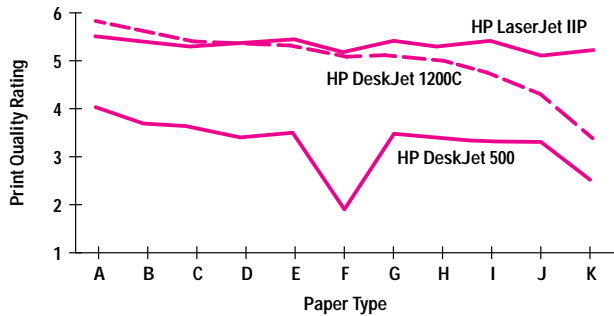


Fig. 10. Print quality of three HP printers for 300-dpi raster text.

The print mode forecaster reads incoming raster data from the language formatter and determines how best to print that data. For example, the forecaster reads ahead enough to decide whether it can print the data in one pass (black only data surrounded by white space) or if the data must be printed in three passes (some color detected or no surrounding white space). In addition, the forecaster detects white space on the page that can be skipped by the print engine. The print engine is notified that these white spaces (on the margins or across the page) can be passed over quickly by sweeping the carriage faster than during printing or by advancing the paper rapidly over the white space. To make these predictions, the forecaster must have enough memory available to store data yet to be printed.

The print engine speed for an inkjet printer is governed by the repetition frequency of each drop generator, the number of drop generators that work in parallel, the rate at which the printer can present the paper to the printhead, and the rate at which ink dries on the paper. Early inkjet printers were mainly limited by the first two factors. It is difficult to increase the stable repetition frequency and still maintain good drop shape, and it is difficult to manufacture large arrays of drop generators working in parallel that all work reliably to produce the optimum print quality. With the DeskJet 1200C, that situation is reversed. The rate at which the media can be moved up to and through the print zone and the rate at which the ink dries on the paper are the limiting factors. Improvements to the paper-moving mechanics reduce the time spent moving the media, and the use of print modes and a heater in the print zone reduce the drying time, increasing the print speed at which high-quality printing can be accomplished.

The production of drops in a thermal inkjet printer involves a complex balance of forces on a very small scale (see "An Inside View of the Drop Generation Process" on page 11). Since surface tension and surface wetting play such dominant roles in the refill process, small variations in these factors can cause chaotic instabilities. The effects of these instabilities can be reduced by controlling the refill speed through fluidic damping and by firing the next vapor bubble piston at a point in the refill process that behaves more consistently than others. The most reliable point of consistency is after a long delay when all the chaotic instabilities have dissipated, but this does not allow the high repetition frequencies desired. The DeskJet 1200C pushes the limits of stability by firing the next drop before the refill from the last has fully damped out. Firing each drop generator before the next charge comes to rest allows a repetition frequency of

8000 Hz. This dynamic point becomes stable only after careful adjustments to the geometry of the fluidic channels that introduce some stability into the chaotic refill process. These channels are constricted in a way that reduces the refill speed and damps the overshoot of the refilling ink front, resulting in a more stable system that is capable of a repetition frequency high enough to remove repetition frequency as a print speed limiting factor.

The effects of this repetition frequency are multiplied by the number of drop generators working in parallel to paint the page. The length of the drop generation array does not come without costs. The more devices the printhead contains in parallel, the higher the probability that a defect can occur in one of them. This risk is reduced by instituting tight control over critical manufacturing processes and by building printhead servicing features into the printer's service station, which help rectify some defects. The printhead size also dictates the length of the print zone in which the printer has to maintain tight control over the media. In the DeskJet 1200C, the media is controlled between a drive roller system and a paper pickup system. The longer the distance between these two, the harder it is to control the media as it is wetted by the drops from the printheads. When the media is first wetted, stresses in the media tend to relax, leading to buckling and cockle. These effects are reduced by the media heating systems and by the control the two media drive rollers exert on the media. The spacing between these two drive rollers allows a printhead array height of one third of an inch, sufficient to print two lines of 12-point text simultaneously in one sweep of the printheads across the page. This helps increase the print speed.

The media handling system of the DeskJet 1200C printer incorporates various mechanical, firmware, and electronic features to increase the printing speed. When the printer receives a print job, the paper is picked by sandwiching it between a platen and rotating rubberized pickwheels. The pickwheels are mounted on a shaft which is driven by a simply mounted stepper motor. The action of the stepper is completely independent of other printer activities. The advantage of this for a multipage document is that the pickwheels can pick a sheet of paper and have it ready and waiting just behind the writing zone while a separate set of rollers ejects the page just printed. A long sheet-feed delay between pages is eliminated. This media handling system can work at full speed or it can be slowed down when the ink density on the page dictates that more drying time (longer time over the heater) is warranted. Customers with low-density output (a page of text) get their pages quickly while those with high-density output (large area fills) still get good print quality without smearing caused by insufficiently dried ink. An additional advantage of moving the paper to just behind the writing zone is that a preheater is located here to precondition the media before it enters the writing zone. The preheater consists of resistive wires embedded in a thin sheet of wear-resistant plastic. The paper is biased against the preheater to provide maximum thermal contact. The effect of the preheater is to dry the paper so that when ink is placed on the paper the heater in the writing zone expends its energy to dry the ink, not the paper. Drying times are cut by 30% by preheating. All this moisture must go somewhere, so a vapor removal system is in place to clear the writing zone of water vapor.

Modifying Office Papers to Improve Inkjet Print Quality

The formulation of paper and the way it is manufactured have an impact on inkjet print quality. Samples of some office papers from three major market regions (North America, Europe, and Asia/Pacific) exhibit variability in black text quality, optical density, color-to-color bleed, color appearance, and mechanical performance. Also observed are changes in the performance of certain paper brands both from sheet to sheet and from ream to ream. This implies that inkjet print quality is not being monitored and controlled during the papermaking process by some manufacturers.

In 1991, Hewlett-Packard created the Office Paper Program to work with the paper industry to improve the inkjet performance of plain paper. Meetings were held with 25 paper manufacturers worldwide to discuss inkjet technology, market growth projections, and print quality issues. A key result of these meetings was a standard-setting document called the Hewlett-Packard Paper Acceptance Criteria for the HP DeskJet 500C Printer.* This document describes minimum print quality specifications for seven key parameters (see Table I) and the corresponding measurement methods. The specifications were set by surveying inkjet printer users in the U.S.A., Europe, and Asia.

The acceptance criteria specifications are being implemented through the Office Paper Program's paper qualification process. After improving inkjet performance (see Fig. 1), paper companies may submit samples for evaluation. These samples

must be taken over specified times and at particular paper machine locations as described in the Office Paper Program's paper sampling guidelines. After imaging with black and color test patterns, the paper sample is measured against the criteria for appearance, mechanical performance, and lack of variability. If the paper is acceptable, it is publicized to existing and potential HP printer customers as a multipurpose office paper qualified for use in all plain paper inkjet products.

As of November 1993, four papers have been qualified worldwide.

David W. Brooks
Development Engineer
Inkjet Supplies Business Unit

* Copies may be obtained from: Hewlett-Packard
Office Paper Program
16399 West Bernardo Drive
M/S 61U50
San Diego CA 92127-1899
U.S.A.

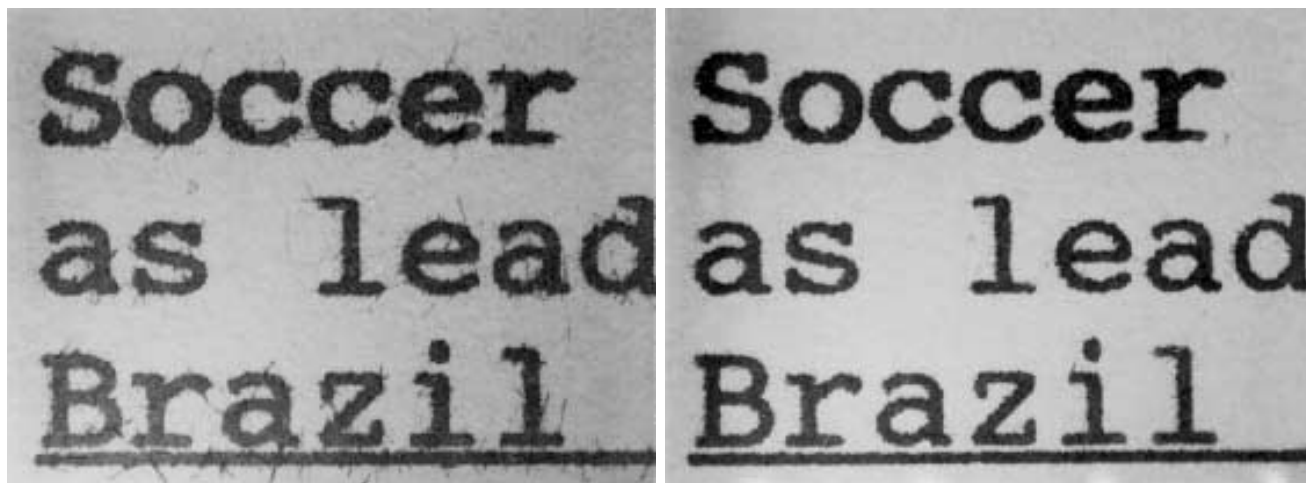


Fig. 1. Samples showing print quality (left) before and (right) after paper improvement.

Other printer features decrease drying time and improve overall print quality. Area fills are more uniform if the heat used to dry them is even over all areas within a printed swath and from swath to swath. To promote this uniformity, the paper is kept in tension during and shortly after printing by the double set of rollers located before and after the writing zone. To further ensure even heating and maximum heat transfer to the paper, a slim piece of sheet metal is pressed against the paper to bias it against the heated writing surface.

While the paper is in the writing zone, the printer performs "smart" printing to increase throughput. The media is quickly advanced over the white space at the top of the page to the first data to be printed. Between sweeps of the print cartridge carriage, the media is advanced to the next data to be printed at the same time as the carriage reverses direction to print the next swath. The length of each sweep is controlled by the forecaster to be only as long as the local margins dictate.

When the drop generators need to be fired periodically into a spittoon to keep them working reliably, no time is lost because that action is smoothly integrated into the carriage sweep motion.

All of the techniques described above, which allow four pages per minute in the highest-quality mode, are further exploited in the highest-speed mode by cutting the number of drops hitting the page in half. The high-quality mode prints at 600-by-300-dpi resolution, which allows the application of HP Resolution Enhancement technology rules to enhance the edge quality of the text characters. The fast mode prints at 300-by-300-dpi resolution, which allows printing each swath at twice the speed. However, since the drop volume for the high-quality mode is tuned for that mode, if the same drop volume were used for the fast mode the text would be too light because of more white space between drops. This problem is reduced by dynamically changing the

Table I
Hewlett-Packard Office Paper Program Minimum Print Quality Specifications and Test Methods

| Parameter | Specification | Text | Method | Reference |
|--------------------------------|------------------------|---------|-------------|--|
| Black | | | | |
| text | ≤ wick #4 | 2.1.2 | visual | figure 1.4 |
| optical density | OD min ≥ 1.2 %D < 8 | 2.2.1 | measurement | |
| mottling | none allowed | 2.2.2.1 | visual | figure 1.5 |
| cascading | none allowed | 2.2.2.2 | visual | figure 1.6 |
| bronzing | none allowed | 2.2.2.3 | visual | |
| Color-to-Color Bleed | | | | |
| black to yellow | until 4/94 < bleed #5 | 3.1.2 | visual | figure 2.3 |
| Color Appearance | | | | |
| red | score > 0 | 3.2.4.1 | measurement | TAPPI T524-om-86 & figures figure 5.1-5.2 |
| yellow | score > 0 | 3.2.4.1 | measurement | figure 6.1-6.2 |
| green | score > 0 | 3.2.4.1 | measurement | figure 7.1-7.2 |
| cyan | score > 0 | 3.2.4.1 | measurement | figure 8.1-8.2 |
| blue | score > 0 | 3.2.4.1 | measurement | figure 9.1-9.2 |
| magenta | score > 0 | 3.2.4.1 | measurement | figure 10.1-10.2 |
| composite black | OD ≥ 0.75 | 3.2.2 | measurement | |
| Mechanical Performance | | | | |
| sheet feed | | 4.1 | operational | |
| missed feeds* | ≤ 2 failures in 1000 | | | |
| multifeeds* | ≤ 2 failures in 1000 | | | |
| jams* | ≤ 1 failure in 1000 | | | |
| *total combined | ≤ 2 failures in 1000 | | | |
| skew | ≤ 0.06 mm/cm | 4.2 | operational | figure 12 |
| wet cockle | ≤ 1 failure in 1000 | 4.3 | operational | figure 12 |
| Black Waterfastness | ΔOD ≤ 0.30 | 5.1 | measurement | figure 13 |
| Black Highlighter Smear | ΔOD ≤ 0.20 | 5.2 | measurement | figure 14 |
| Lightfastness | | | | |
| black | ΔE* ≤ 10 | 5.3 | measurement | figure 15 TAPPI T524-om-86 |
| red | ΔE* ≤ 60 | 5.3 | measurement | TAPPI T524-om-86 |
| green | ΔE* ≤ 50 | 5.3 | measurement | TAPPI T524-om-86 |
| blue | ΔE* ≤ 70 | 5.3 | measurement | TAPPI T524-om-86 |
| cyan | ΔE* ≤ 60 | 5.3 | measurement | TAPPI T524-om-86 |
| yellow | ΔE* ≤ 30 | 5.3 | measurement | TAPPI T524-om-86 |
| magenta | ΔE* ≤ 85 | 5.3 | measurement | TAPPI T524-om-86 |
| composite black | ΔE* ≤ 50 | 5.3 | measurement | TAPPI T524-om-86 |

Note: All references to text and figures in this table pertain to the Hewlett-Packard Acceptance Criteria for the HP DeskJet 500C Printer.

drop volume between these two print modes. The drop volume is increased for the fast mode by increasing the control temperature used in the printhead temperature control process. The higher the printhead temperature, the larger the drops become. The resulting increase in dot size on the paper provides good print quality at six pages per minute with the same printhead that can do four pages per minute in the highest-quality mode.

Acknowledgments

This article was written by the members of the black print quality seam team, representing ink chemists, print cartridge architects, printer firmware engineers, and printer quality engineers. There was a considerable focus on output quality during the program by everyone in both the print cartridge and printer programs, as well as the support areas such as

the ink lab, print cartridge test area, system test group, ICDC proto, and the model shop. It would be impossible to individually acknowledge the support of all of the people without inadvertently leaving someone out. But to all of these people, we would like to express our appreciation for the contributions each of you made to the success of the program.

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High-Quality Inkjet Color Graphics Performance on Plain Paper

Realizing the color graphics performance of the HP DeskJet 1200C printer required simultaneous optimization of many interacting parameters of the ink and the architecture to deliver significant improvements in print quality, color gamut, throughput, and cost per copy.

by Catherine B. Hunt, Ronald A. Askeland, Leonard Slevin, and Keshava A. Prasad

The HP DeskJet 1200C printer is a 300-dpi, plain paper printer that provides vivid, bright, true colors with consistent print quality on all media (plain and special papers, transparency and glossy films).

The color print cartridges (cyan, magenta, yellow) for the DeskJet 1200C represent a significant advance in HP thermal inkjet printing technology. The major contributors to the improved performance, print quality attributes, and throughput are the ink and the architecture. Both the ink and the architecture were optimized to deliver significant improvements in print quality, color gamut, throughput, and cost per copy. One major customer benefit of the DeskJet 1200C cartridge is the small drop volume, which provides industry-leading color cost per copy at any use rate.

During the color development phase of the DeskJet 1200C printer, the HP DeskJet 500C¹ and HP PaintJet XL300 printers were used as benchmarks for color graphics. The team learned a great deal from these products and leveraged some of the acquired knowledge in developing a significantly better product. However, leveraging from these products did not make the development easy; a major effort was still required since new issues emerged as design modifications were made. Test qualification became very important, and since time was a limiting factor, the design-build-test-fix cycle became a challenge. Throughout the project, optimization was done within aggressive schedule objectives.

Addressing Customer Needs

Early in the DeskJet 1200C printer and pen cartridge development, the QFD (Quality Function Deployment) method of addressing customer needs was used.² This established a foundation of customer focus throughout the project for both the printer and the print cartridge.

A QFD team was formed to gather customer needs, link one or more engineering metrics to the customer needs, and determine what technical factors engineers could control and measure to satisfy the customer needs. This team was composed of representatives from different areas of the project.

Based on the QFD customer research studies, several fundamental characteristics that define color graphics quality were identified:



Fig. 1. Drop placement errors caused by swath advance.

- Color quality
- Area fill quality
- Line and edge quality
- Cockle
- Curl
- Whiteness
- Archivability.

Engineering Metrics

Color quality of a printed output is determined using the Munsell color measurement system.³ Chroma is a measure of the vividness or brightness of the color. Hue refers to the shade or tone of the color. Value is a measure of the darkness or lightness of the color. The color gamut describes this three-dimensional color space:

$$\text{Color Gamut} = \text{Value} \times \text{Chroma}^2 \times \text{Hue}.$$

Customer survey results indicate that smooth area fills are very desirable. The parameters that can affect area fill quality are:

- Drop placement errors caused by swath advance (see Fig. 1) and theta-Z (printhead rotational misalignment) errors

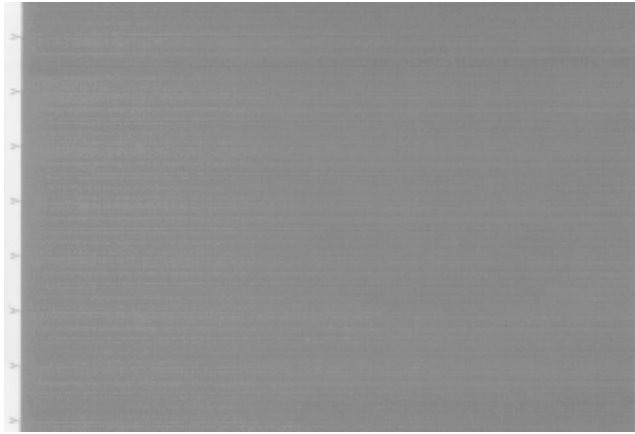


Fig. 2. Banding caused by misdirection.

- Banding caused by pen defects such as misdirection (see Fig. 2) and variations in drop volume or dot size
- Wait time banding (see Fig. 3)
- Mottling (see Fig. 4)
- Bleed caused by different penetration rates of the ink into the media (see Fig. 5)
- Coalescence caused by drops pulling together before the printing surface is wetted
- Print rendering methods.

Mottling, coalescence, and wait time banding are evaluated visually. Several algorithms using a machine vision system were developed to measure swath advance and theta-Z errors, directionality, dot size, and bleed.

Artifacts such as spray (see Fig. 6), feathering, and jaggy horizontal and vertical lines (see Fig. 7) caused by dot placement errors or paper shrinkage can deteriorate the line and edge quality of the printed image. Spray is inherent in thermal inkjet technology and it is made worse by the presence of the vapor removal system in the printer. The vapor removal system consists of the fan and the plenum. Its primary function is to remove local moisture from the writing system area.

Flat paper output is another customer want. Paper cockle is a distortion in which bumps or ridges are randomly produced

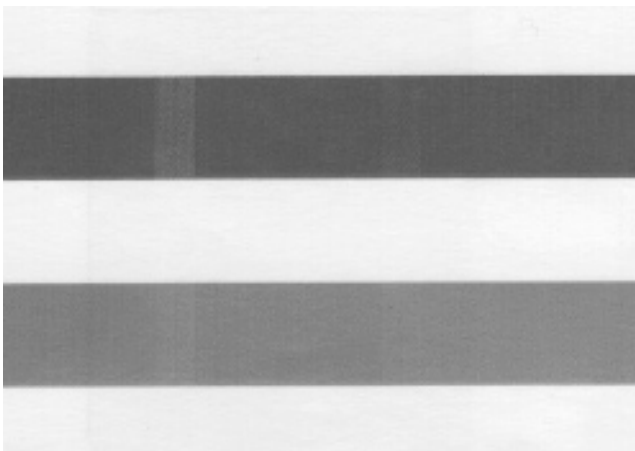


Fig. 3. Wait time banding.

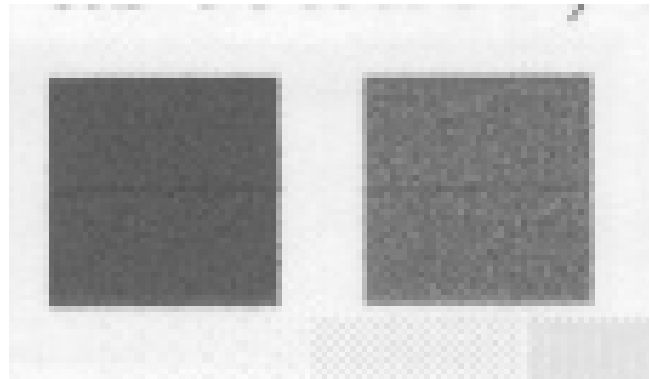


Fig. 4. Mottling.

on the printed paper. Paper flatness is lost and the output has a wavy appearance. This is a side effect of high-density inkjet printing with aqueous inks. Visual measurement is done on paper cockle. Curl is a phenomenon in which the edges of the paper migrate towards the center of the paper (see Fig. 8). In worst-case environmental and printing conditions, the output may take the form of a tube. Curl measurements involve measuring the height of all four corners of a sample resting on a flat surface. This problem can be a major customer dissatisfier since paper curl affects media stacking and curled sheets are difficult to display or store. Cockle and curl get worse as the throughput increases. These print quality defects are inversely related. The more cockle a solid area fill output has, the less curl it has. The cockle appears to reinforce the paper so that it does not curl.

Fig. 9 shows one of the engineering test plots used to evaluate some of the print quality attributes such as dot size, line width, color quality, banding, and mottling.

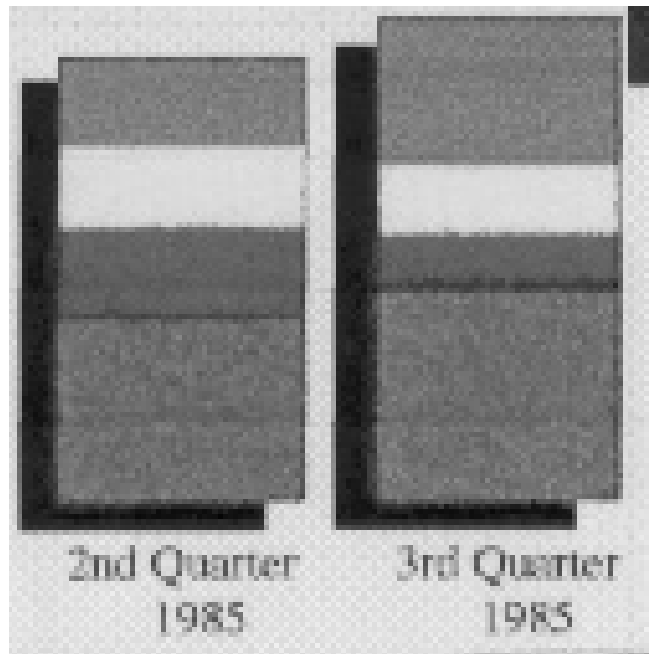


Fig. 5. Bleed.

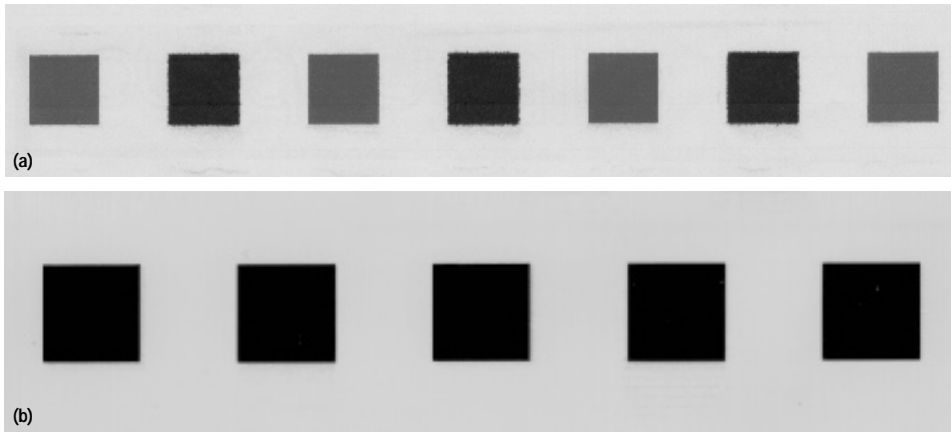


Fig. 6. (a) Spray. (b) Shim spray.

The amount of ink placed on the media is a very important parameter to control since it affects several print quality attributes such as bleed, transparency film bleed and blocking,* glossy film bleed and color transfer, cockle, curl, and banding. To achieve acceptable edge acuity and area fill quality for color graphics, the size, shape, and consistency of the drops fired from the printhead generator need to be controlled. Drop volume is an engineering measurement used to determine the amount of ink delivered by the print cartridge in a single drop. Dot size and shape are engineering measurements used to determine the size and shape of the spot made by a drop of ink when it lands on the paper. The print cartridge architecture is an important print cartridge parameter that, in conjunction with the ink, controls these attributes.

Color Architecture and Drop Volume

Selecting the target drop volume was an important part of the architecture design process. This was critical to system testing to determine ink, media, heater, blower, and print-mode interactions. Several product and print cartridge variables were considered in selecting the target drop volume. The product variables were:

- Heater settings. Higher temperatures increase the delivered volumes but decrease the dot size for a given drop volume.
- Print cartridge temperature. The print cartridge temperature increases with continuous printing and this increases the delivered volume.
- Print mode. The amount of ink placed in different passes changes the dot size and the area fill coverage.

* Blocking is a phenomenon in which the ink and media stick to the plastic sleeves used to protect transparencies, causing pockets of air that cause distorted images when the film is projected.

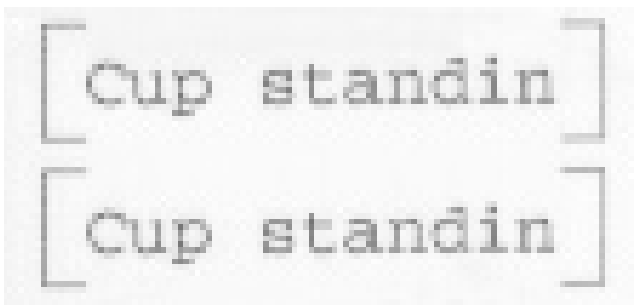


Fig. 7. Jagged lines.

- Swath advance accuracy. Larger dot sizes are required if swath advance errors are large.
- High-density versus low-density plots. High-density plots hide artifacts such as directionality, but induce problems such as curl, cockle, bleed, transparency film bleed and blocking, and glossy film bleed and image transfer.
- Special paper versus plain paper. Special paper must typically print in the same print modes as plain paper. The challenge was to obtain the same dot size as closely as possible for both media.

The print cartridge variables that were considered are:

- Ink. Different inks have different dot size characteristics because of heater settings, ink penetration rates, and print cartridge temperatures.
- Directionality. Larger spots are needed to cover larger errors.
- Manufacturing variability. Large drop volumes affect the area fill quality, cockle, bleed, transparency film bleed and blocking, and glossy film bleed and image transfer. Low drop volumes show artifacts such as misdirection and improper color saturation.

As mentioned earlier, the small drop volume delivered by the HP DeskJet 1200C color print cartridge provides very low color cost per copy. When pulse warming was implemented in the DeskJet 1200C as explained in the article on page NO TAG, the nominal drop volume was lowered by about 5



Fig. 8. Curl.

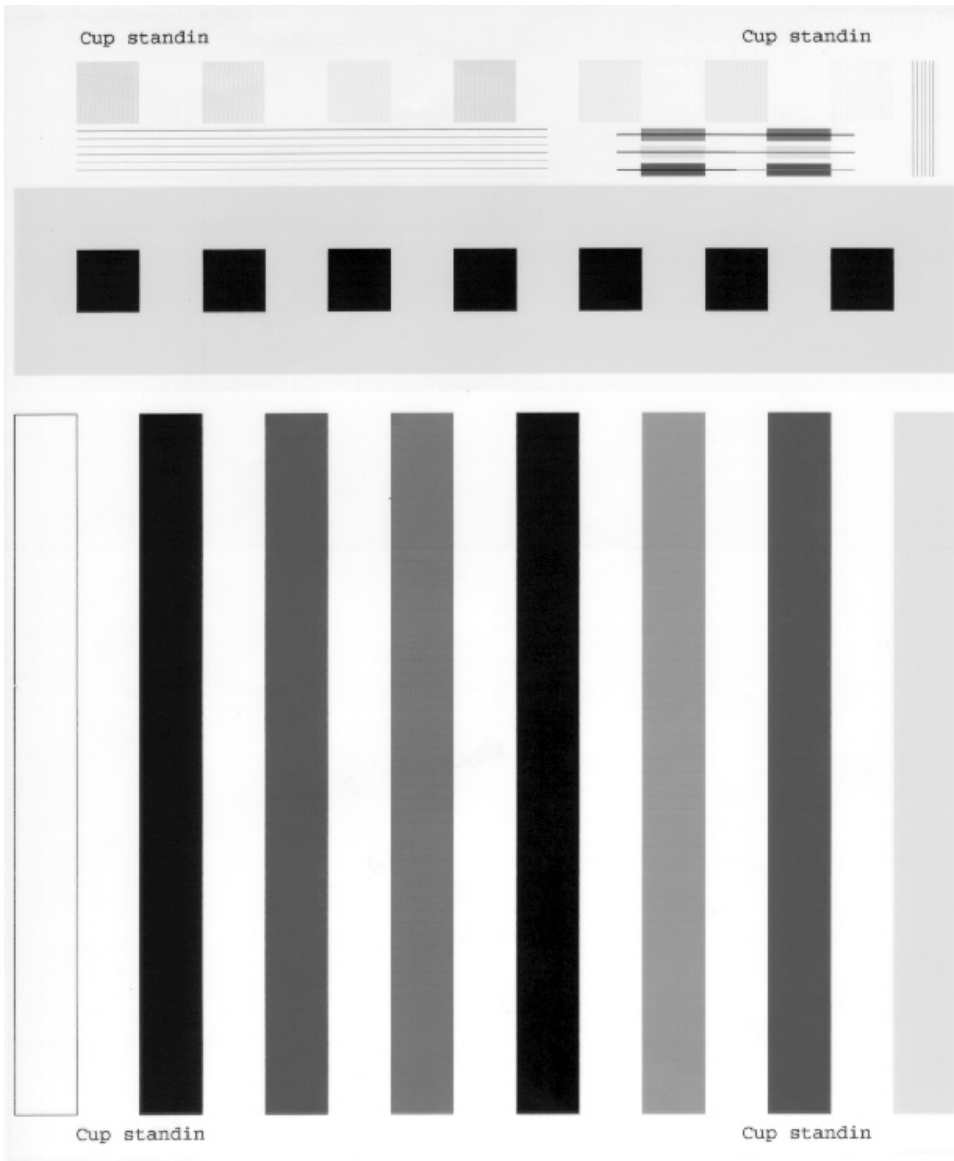


Fig. 9. Print quality metric plot.

picoliters. Changes in the orifice diameter, resistor size, and barrier geometry were required to implement and compensate for this change.

One of the challenges of designing the color architecture was to be able fire the print cartridge at a higher frequency. This was driven by the customer need for increased throughput. As the frequency was increased, puddling also increased (see Fig. 10), and ink accumulated on the surface of the top plate, causing misdirected drops called streaks (see Fig. 11). To correct these problems, a balance between refill speed and fluid damping was incorporated in the architecture design by adjusting the dimensions of the channel.

Print Mode

Achieving high color graphics throughput (less than two minutes per page for high-quality print mode on a range of plain papers and three minutes per page for transparency and glossy films) was a very challenging customer demand. To achieve this aggressive goal, the amount of ink placed on the media per dot location, the speed with which the ink is placed, and the number of passes required to complete the

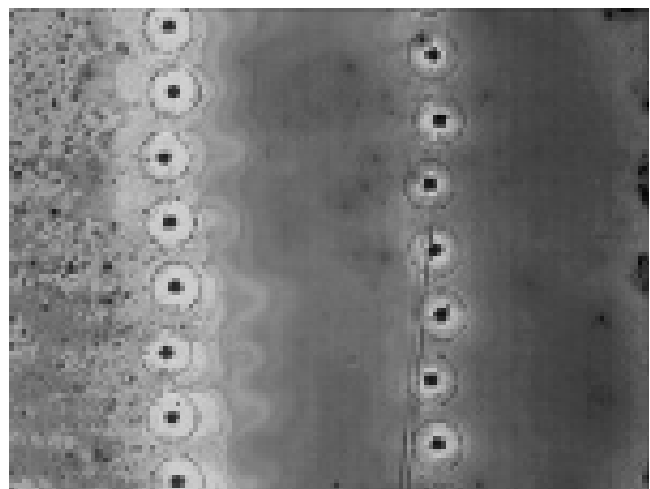


Fig. 10. Puddling.

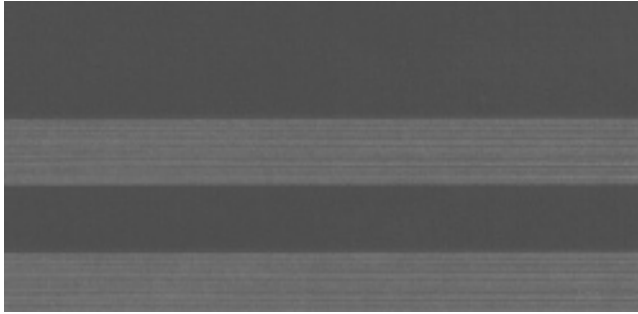


Fig. 11. Streaks.

image became very critical factors. The print mode is the mechanism used to control these factors. The choice of print modes had a large impact on certain key design decisions such as swath advance distances for greatest accuracy, swath advance accuracy goals, and electronic architecture. The print mode has a tremendous effect on print quality attributes such as bleed, cockle, banding, edge acuity, spray, color saturation, curl, transparency bleed and blocking, and glossy film bleed and image transfer.

Two print modes were considered for high-quality special and plain media printing: four-pass at a higher scan speed and three-pass at a slower scan speed. The three-pass mode was chosen because it has several advantages over the four-pass mode. The slower scan speed produces less spray and smaller ink-drop tails because the print cartridge is fired at a lower frequency. This also avoids streaks or misdirectionality since puddling is reduced. Paper curl is better since the paper spends more time over the heater. One advantage of the four-pass print mode is to reduce cockle, since the ink density per pass is lower.

One of the biggest decisions in print mode development was the implementation of transparency and glossy print modes. Transparency film bleed and blocking and glossy film bleed and image transfer were major problems faced by the color technical teams. These problems are accelerated at high temperatures and humidities. The print mode developed for glossy and transparency film uses six passes with one third of the ink density placed per pass, completing 100% area fill density after the third pass and 200% density after the sixth. A special print mode algorithm varies the amount of ink placed per pixel for primary and secondary colors. For example, to print green on transparency film, one drop each of yellow and cyan are used in each of two opposite corners of a pixel and one drop of yellow and two drops of cyan are used in each of the remaining corners of the pixel.

System Test Strategy

The color development team was constantly battling to improve print quality, reliability, throughput, and cost. The challenge of providing the best print quality with high performance at a reasonable price to attract both home and business customers was constantly faced. These customer demands became increasingly difficult to meet. Any design modifications made to improve one of these areas was bound to affect one or more other areas adversely. The technical team needed to ensure that the components of the system were properly integrated.

The DeskJet 1200C writing system is complex. Its major components are the printer, the cartridge, and the media. The printer consists of the heater, the blower, the electrical system, the print algorithms in firmware, and the service station. The print cartridge consists of the ink, the architecture, and the ink delivery system. The media types include special and plain paper and transparency and glossy film.

A system approach to setting objectives and problem solving was the key to optimizing system performance while minimizing time to market. Understanding component-level design issues and how they affected the system as a whole was important since it saved time, effort, and resources. As mentioned earlier, time was a limiting factor in the development of the DeskJet 1200C printer and print cartridge. Shortening the design-build-test-fix cycle and meeting the design objectives became a real challenge. Any design changes required a series of design iterations, each with a long lead time, followed by an intense qualification phase. System test development became a vital part of the development phase.

Ambient and Environmental System Test

The purpose of the system test was to screen new designs, processes, or ink and media formulations quickly and identify failures or areas of concern. The test was designed not only to test for conformance to specifications but also to test for failures. This test measured the print quality and reliability of the system. It was important to monitor both print quality and reliability since a system with poor reliability can lead to unacceptable print quality.

The test consisted of both user and diagnostic plots using different print modes and media. The print quality attributes evaluated were dot size, line width, drying time, water fastness, smear fastness, archivability, color quality, bleed, cockle, spray, feathering, banding, and curl. The reliability attributes evaluated were intervention rate, failure rate, short-term decap time,* and start-up.

Print Quality Evaluation

During color development, we found it necessary and beneficial to use our HP division's internal print quality committee. The print quality committee represents the end user's opinions, and research has been done to show that the print quality committee correlates very well with our end users in most cases. The committee was initially used to determine how the DeskJet 1200C compared to the benchmark products. It was also used to judge the acceptability limit of a single print quality attribute at a time. This provided quick feedback on improvements without extensive outside market research, which adds cost.

A vision system tool was also used to measure dot size, directionality, bleed, line width, and color quality (chroma, hue, gamut). As new problems emerged, it became necessary to develop tests and metrics to determine the severity of the problems.

* Short-term decap time is the amount of time that a print cartridge can be left uncapped and still recover. When a cartridge is left uncapped the water in the ink evaporates, leaving very viscous ink around the nozzles. This can cause nozzles to drop out (fail to function).

Issues and Trade-offs

The color graphics seam team faced many issues and trade-offs during the development phase.

To achieve the throughput goals that were set for the HP DeskJet 1200C printer, a heater was added to accelerate the drying of the ink on the surface of the media. This minimizes the amount of cockle and bleed on the output. However, the use of the heater has the disadvantage of making paper curl worse. After extensive investigation, the ink was found to be the major factor that could be controlled to solve the problem. The DeskJet 1200C ink contains an anticurl agent to provide curl-free high-density output at high throughput.

The introduction of the new ink was not without its set of other problems. After a series of system test qualifications, one of the major problems found was an archival problem. The mechanism that helps reduce paper curl had a negative effect on transparency and glossy film. Transparency bleed and blocking and glossy film bleed and color transfer were unacceptable, especially at worst-case environmental and printing conditions. The problem also got worse over time. During our ink vehicle optimization investigation, we found that there were no margins for changing the ink to achieve acceptable print quality on both film and curl issues. In our investigation, we had identified several possible solutions: (1) adjust the heat, (2) modify the time over the heater, (3) change the drop volume, (4) change the inks, (5) change the films, and (6) use a different print mode that places less ink on the film. To improve the film issue without compromising curl and other print quality attributes, the film and the amount of ink on the film were found to be the major controllable factors. A major film development effort was spearheaded by the media team (see article, page NO TAG) and print mode development was put into place to control the amount of ink on the film without compromising color quality.

Color Ink Development Process

The aggressive schedule for the DeskJet 1200C required quick development of color inks that met all design objectives. The approach was to follow three relatively simple principles: listen to the customer, communicate changes, and don't try to do everything yourself. The development of the DeskJet 1200C color inks followed the QFD approach² to listen to the needs of the customer. Key attributes for color ink design were:

- Large color gamut
- Excellent red chroma on plain paper
- Bright colors
- High-speed printing
- Excellent quality on a variety of media
- Low ink cost per page.

Meeting aggressive time-to-market goals required selecting a technical path for color ink development without knowing all of the possible problems associated with that path. The approach taken was to divide ink requirements into "must" and "want" objectives. Musts were things that the product had to have and were nonnegotiable, while wants were important but not essential. Examples of musts are reliability and nontoxicity. Examples of wants are low cost per copy, light fastness, high throughput, and low cost. Some attributes had both must and want objectives. For example, the

must objective for color gamut was to equal the gamut of printers on the market, while the want objective was to exceed other printers.

Several color ink development pathways were evaluated to see if they met the must objectives. Pathways that failed to meet one or more musts were rejected and the surviving pathways were evaluated to see how well they met the want objectives. A problem was encountered because all wants were not equal—some were more important than others. Instead of relying on the technical team's ability to prioritize want objectives, the QFD approach was used. QFD not only ranks customer needs by order of importance, but can also be used as a tool to see how well technical tests match the attributes that customers care about. For example, instruments can be used to measure color coordinates in CIE color space, but this wouldn't have any meaning to the average customer. What the customer understands are terms such as bright colors, saturated images, and vividness. By looking at the matrix of how customer needs are ranked and how well analytical tests match those needs, want objectives were prioritized and the correct ink development path was chosen.

As ink improvements were made during the DeskJet 1200C program, it was important to communicate ink changes clearly to the rest of the project teams. There was always a default color ink set, which allowed the program to move forward. As new ink formulations were evaluated, their performance was compared to the default ink. When a new ink had been thoroughly tested and exceeded the performance of the default, the default ink was changed to the next ink revision. To avoid confusion, the entire set of three color inks was changed to a new revision, even if only one of the three inks was changed.

Hewlett-Packard's ink development resources were leveraged by working closely with a partner for ink development and manufacturing. Having a partnership as opposed to a vendor-customer relationship had numerous advantages and provided a few additional challenges. Some of the advantages included the ability to carry out custom synthesis of new compounds, access to facilities and equipment, and the availability of a large chemistry knowledge base to help solve problems.

By working with the same partner for both R&D and manufacturing, the team was able to achieve a smooth transition from development to production. Many of the same people involved in ink design were also involved in setting up the manufacturing facility. This increased the focus on using manufacturable processes as the inks were developed. The same or similar manufacturing equipment was used to provide ink for R&D and for full-scale production. This greatly simplified scaling up to production levels and the transition from R&D to manufacturing.

Some of the challenges of working with a partner as opposed to a vendor were more frequent travel and meetings and a greater need for clear communication of goals and expectations. Different corporate cultures were also encountered and each group had to learn the other's terminology. The advantages of a partnership clearly outweighed the disadvantages and allowed the team to meet customer needs.

Color Ink Design

In designing an ink, one begins by setting its performance requirements based on user needs and the restrictions imposed by the printer's hardware and operating conditions. For the DeskJet 1200C printer, the user needs were low cost and high-quality graphics at fast throughput rates. The ink that was designed to meet these user needs consists of dyes and a vehicle. The dyes impart a gamut of bright, saturated colors. The vehicle provides:

- A carrier for the colorant into the paper fibers
- Fast drying time to allow faster throughput
- Anticrusting properties to prevent clogging of the nozzles in the print cartridge
- Dot spread for lower cost per copy
- Anticurl properties to allow printing of high-density graphics
- Fluid dynamics for reliable drop ejection
- Biocides for control of microbial growth.

Ideally, each functional requirement would be uniquely influenced by one component in the ink formulation, but in reality, any given component can play multiple roles, both positive and negative. A further complication is that the functional requirements place conflicting demands on the ink, and the hope is that the individual operating windows will overlap with sufficient latitude. The concentration of each component is optimized and an operating window is assigned through rigorous system testing. The optimized formulation and the tolerances are then translated into a set of measurable physical properties of the ink. In the beginning, this set may be incomplete and have wide specification ranges, but as the project matures, more parameters enter into the picture and the ranges tighten. The resulting formulation and specifications are then passed on to manufacturing which formulates the production quality plan.

Dye Selection

The dye choices for cyan, magenta, and yellow were driven by the customer expectations of vivid, bright colors on varied media, as well as by the need for more color. The initial choice for these three dyes was to use the well-established dyes already in use in HP plotter print cartridges and in already released HP DeskJet printers such as the DeskJet 500C. These anionic dyes have well-characterized archival properties, and when coupled with the appropriate counterion (cation), can be made compatible with all the performance and reliability requirements of the new cosolvent ink writing system.

Purity of the dye sources can effect color significantly. To ensure purity, physical properties of the inks, such as conductivity, pH, anion and cation concentrations, viscosity, surface tension, and UV-visible spectra must be tightly specified and monitored.

Color Optimization

The customer need for vivid, bright colors on varied media determined the choice of color metrics to be used in determining dye loads.

First of all, it was decided that the metric should be based on a visual system such as the Munsell system³ rather than an instrumental system such as $L^*a^*b^*$ ⁴ (more about this later). Therefore, all instrumental measurements were transformed from $L^*a^*b^*$ coordinates to Munsell coordinates.

Second, the metric was further refined by scaling Munsell color differences according to the Balinkin transformation,⁵ which reflects the actual human response to the variables. The Balinkin-scaled chroma difference is $20\Delta C/\pi$, where ΔC is the Munsell chroma difference, while the Balinkin-scaled hue angle difference is $2C\Delta H/5$, where ΔH is the Munsell hue difference.

The method used in optimizing dye loads was as follows:

- Identify a set of focal colors to be used for measurements.
- Determine the Munsell coordinates of the focal colors chosen.
- Adjust dye loads to exceed the Munsell chroma of the focal colors while matching the Munsell hue and value of the standard colors.

Focal colors are colors for which people, independent of culture, identify a one-to-one correspondence between the color names and definite regions in 3D color space. The centroids of focal color regions such as red, orange, green, yellow, purple, pink, and brown have been determined.^{6,7} The intersection of the focal colors with the color secondaries RGB (red, green, blue) and the color primaries CYM (cyan, yellow, magenta) results in four colors: RGBY. These were selected as the colors to be measured for dye load optimization. In Munsell color coordinates the focal color centroids are as shown in Table I.

Table I
Focal Color Centroids in Munsell Coordinates

| | Hue | Value | Chroma |
|--------|-------|-------|--------|
| Red | 5.6R | 4.6 | 13.2 |
| Green | 2.8G | 5.2 | 10.3 |
| Blue | 6.4PB | 4.1 | 9.2 |
| Yellow | 6.4Y | 9.0 | 12.8 |

Note: The Munsell hue spectrum is circular and is divided into ten regions, each of which is divided into ten angle units called hundredths. A color's hue is specified by a letter code identifying the region and a number between 0 and 10 indicating the number of hundredths within that region.

The color metric used to measure the goodness of each ink color was:

$$\text{Metric} = 20\Delta C/\pi - |2C\Delta H/5|,$$

where ΔC is the chroma excess, or the amount by which the chroma of the ink color exceeds the chroma of the focal color centroid, and ΔH is the hue angle deficiency, or the amount by which the ink color differs from the hue of the focal color centroid. Thus the metric is the Balinkin-scaled chroma excess minus the absolute value of the Balinkin-scaled hue angle deficiency. This metric reflects the relative importance of chroma excess and hue angle deficiency relative to the centroids.

However, selection of a metric was only the beginning. Because the results could be expected to be influenced both by the type of media and by the specific color, the optimization procedure also needed to reflect the relative weightings of the focal colors and of the various required media. Using QFD and Kepner-Tregoe⁸ approaches suggested the following rankings of importance from the customer standpoint:

Media: Office Papers > Transparency Film > Special Papers

Focal Colors: Red > Yellow > Green > Blue.

Dye loads were optimized by maximizing the metric for the focal colors using these relative weightings to make trade-offs where necessary.

Other Optimizations

In addition to this quadratic design optimization of the Balinkin-scaled metric (excess chroma minus hue difference) by adjustment of dye loads, a second factorial design optimization was performed. Optimal concentrations of red magenta dye to be mixed with the original violet magenta dye to obtain the optimum chroma-hue balance in the red and blue focal colors were determined. The original magenta dye, when used alone, created reds that were too violet in hue but created excellent blues. The second magenta dye, when used alone, created reds that were too orange in hue and created blues that were both too dark and too achromatic. The factorial optimization coupled with the quadratic optimization simultaneously created the best balance in both the red and the blue focal color regions.

Optimization of the third coordinate of color, which is value, or lightness/darkness, is implicit in the optimization described above, since the chroma optimization can only be made after an initial dye load approximation to give proper optical density, adjusting for drop volume, dot spread, print mode, heater settings, and media differences. However, increasing dye load to increase chroma also tends to increase value. This was only a problem with the blue focal color, which came out slightly too dark, but the result was judged to be within the acceptable range.

Another useful metric for optimization is the Munsell gamut number, which has the dimensions (value \times chroma² \times hue) and is an acceptable metric describing the entire 3D accessible color space using a black print cartridge and white media difference to describe the extreme value difference. The disadvantage in the use of this metric is that the color gamut is dependent upon the black ink and may not reflect the customer need for more vivid, bright colors. We used the Munsell gamut as a check on our other methods and found, as expected, that gamut was increased by our optimization methods.

Results of Color Optimization

To illustrate the success of these techniques of optimization, consider the focal color coordinates of the optimized DeskJet 1200C color ink on just one of the copy papers, as shown in Table II. Singling out one type of media is representative of the solution, but of course, the weighting factors for all media were considered in the total optimization.

This oversimplified analysis points out that the metric is positive for R, G, B. Only the value of the blue focal color is very different from target (2.9 in Table II versus 4.1 in Table I). The red and the green hues on this type of media are very slightly yellow, but the added chroma benefit more than exceeds that slight hue error (less than one hundredth of a Munsell hue circle). Furthermore, dithering a slightly orange red with a magenta of the same value to obtain optimum reds is less obtrusive than dithering too bluish a red with a yellow of far higher value to obtain optimum bright reds.

Table II
HP DeskJet 1200C Ink Coordinates and Focal Color Differences on One Copy Paper

| | Hue | Value | Chroma | ΔC | ΔH | Scaled Metric |
|---------|-------|-------|--------|------------|------------|---------------|
| Red | 6.5R | 4.8 | 14.4 | 7.6 | 5.2 | 2.4 |
| Green | 1.7G | 5.1 | 12.0 | 10.8 | 5.3 | 5.5 |
| Blue | 8.6PB | 2.9 | 12.0 | 17.8 | 10.6 | 7.2 |
| Yellow | 6.9Y | 9.1 | 13.0 | 1.3 | 2.6 | -1.3 |
| Magenta | 3.1RP | 5.0 | 17.0 | | | |
| Cyan | 7.2B | 5.9 | 12.0 | | | |

The yellow hue is slightly greenish, but the resulting scaled hue error is too small to be significant.

Since the primaries and secondaries all exceed the requirements for chroma, the resulting gamut of available colors compares very favorably to the gamuts of competitive inkjet and thermal transfer products (see Fig. 12).

L*a*b* versus Balinkin Coordinates

The need to transform from L*a*b* coordinates to Balinkin coordinates is illustrated by Fig. 13, which shows the dependency of the L*a*b* color difference metric $\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$ on the hue, value, and chroma of all six color primaries and secondaries. For convenience, a constant delta Balinkin of 6 has been chosen as a frame of reference, and fading of each of these six colors has been simulated in each of the separate three coordinates of color: hue, value, and chroma. Note that human observers are most sensitive to changes in ΔE^* resulting from chroma loss and least sensitive to changes resulting from value gain (lighter). ΔE^* changes resulting from hue shifts are very dependent upon initial hue, being most sensitive in yellow and least sensitive in blue and magenta. In summary, ΔE^* as a metric is more of a historical and instrumental convenience than it is a consistent metric for human visual response.

Vehicle Design

In addition to providing high-quality graphics, the HP DeskJet 1200C printer had to be faster than the HP PaintJet

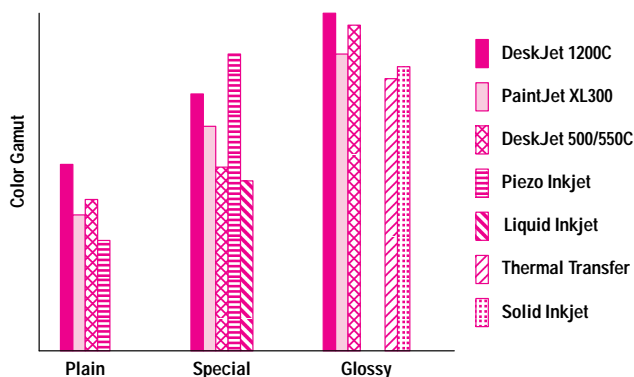


Fig. 12. Relative color gamut of the HP DeskJet 1200C printer and other color printers.

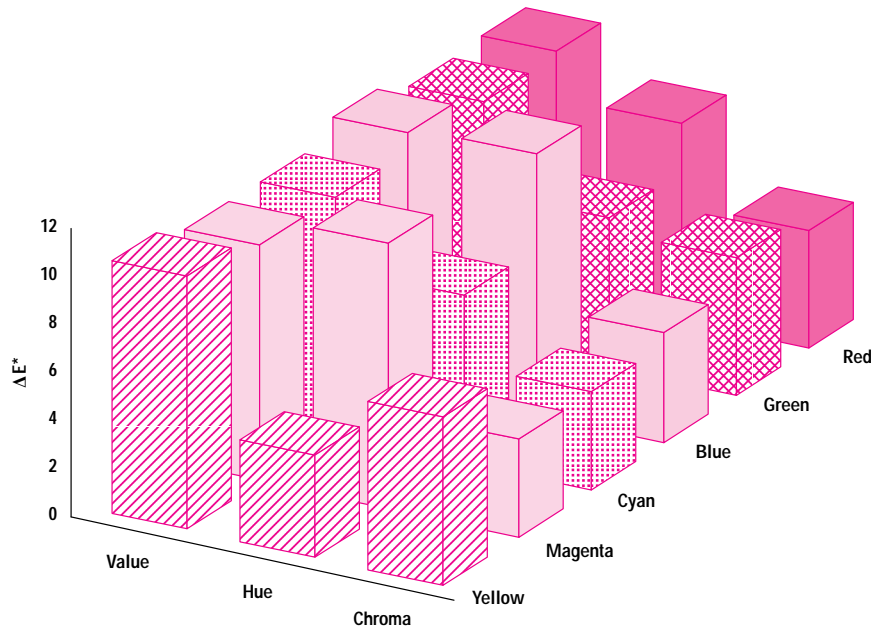


Fig. 13. Relative effect on the L*a*b* metric ΔE^* of constant perceptual changes in value only, hue only, or chroma only as a function of original color for the primaries C,M,Y and secondaries R,G,B.

XL300 printer. The throughput goal was specified at less than two minutes for a high-density plot on office paper. The throughput for the HP PaintJet XL300 printer at equivalent density is three minutes per page. To meet this goal required a system approach involving the ink, print cartridge, media, and product. However, this section will focus mainly on changes to the ink.

To achieve the throughput goals, the color inks had to be designed for faster penetration into the paper to avoid bleeding or mixing of colors between adjacent drops. The penetration is usually driven by capillary pressure, although in some papers penetration is controlled by diffusion. The classical Lucas-Washburn⁹ model is used to first order to describe the water transport in the pore system of the paper:

$$L = \left(\frac{r\sigma \cos \theta}{2\eta} \right)^{1/2} t^{1/2}$$

where L is the penetration distance after time t, r is the pore radius, σ is surface tension, θ is the contact angle, and η is viscosity.

However, this equation does not take into account the dynamic nature of capillary pressure (surface tension and contact angle) or of pore radius which changes because of swelling of the paper fibers upon absorption of water. Nonetheless, it does provide an important piece of information: that faster penetration can be achieved by reducing the contact angle* (increase wettability) between the ink and the paper surface as well as by reducing the viscosity of the fluid.

Most paper surfaces are hydrophobic (they repel water). Thus, surface-active agents (surfactants or cosolvents) were added to improve the wettability of the ink to the paper. Reducing the wetting delay time allows faster penetration into the paper. However, it was later discovered that an adverse consequence of faster penetration is severe paper curl on high-density color plots. It was subsequently determined to be caused by interaction of the printer's heater and the ink. Initially, the issue of paper curl was addressed mainly by the

printer design group because significant changes to the inks at this phase of the product cycle was viewed as risky. When the plausible printer fixes were unsuccessful in eliminating paper curl, the inks became involved in the solution.

Knowing that paper curl results from stresses caused by differential shrinkage (from water absorption and subsequent evaporation) of paper fibers between the wet printed side and the undisturbed fibers on the back side, the ink strategy for fixing curl focused on replacement of the water in the ink with alternate additives or cosolvents. Soon it was learned that compounds with a particular type of attraction with the paper fiber were most effective. The higher the concentration of organic additives, the lower the amount of paper curl.

However, the amount of organics that could be added was constrained by the performance on transparency film. These constraints, especially at high temperature and high humidity, were the amount of bleed or mixing between adjacent drops and film blocking. Therefore, an ideal compound was not only effective but more efficient in controlling paper curl. However, even with the best anticurl substance, an acceptable trade-off between paper curl and transparency film performance required modifications to the film coating.

In addition to the paper curl issue, the use of surface active agents to lower surface tension and increase wettability created another issue known as puddling (see Fig. 10). These puddles are formed by overshoot of the ink meniscus in the print cartridge chamber during drop firing. As the puddles accumulate on the nozzle plate, they interfere with drop ejection, leading to misdirected or missing drops. Print cartridge architectures with increased damping combined with inks containing special polymers to reduce puddling were incorporated for reliable printing in high-quality mode (2-kHz firing rate).

Dot Spread

Low ink cost per copy is increasingly becoming an important competitive advantage. The HP DeskJet 1200C goal was less than U.S. \$0.10 per copy at 15% density. To achieve this goal

* See page NO TAG for the definition of contact angle.

required a print cartridge drop volume range half that of previous HP printers with 300 dots/inch (dpi) resolution (about 120- μ m dot diameter). To attain the same dot size for 300 dpi but at half the typical drop volume required a significant change in ink properties. It turned out that, in addition to providing improved bleed performance on paper as mentioned earlier, surface-active agents provide an added benefit. In a given print cartridge architecture, an ink containing a surface-active agent produces a larger dot than an ink with no surface-active agent. The greater lateral spreading of these drops is a direct result of greater wettability of the ink to the paper fibers. A negative side effect is a slight loss in text edge acuity on some papers.

Acknowledgments

A project of this breadth and complexity had many contributors. The success of this project was mainly because of the great team effort exhibited by the group. We would like to thank the DeskJet 1200C printer team and the inkjet R&D and production teams for their dedication and support. We would like to acknowledge our management team for providing a creative, productive, and supportive environment. We would also like to acknowledge the members of the QFD and seam teams for a job well done. Special thanks to Chuck

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Polyester Media Development for Inkjet Printers

A discussion of the mechanisms and ink/printer/media interactions that must be considered in the design of special media for a printer system, and of the methods available for optimizing them.

by **Daniel L. Briley**

The full capability of a printer system is best realized by printing on special media designed and developed to work on that specific printer system. HP special media include the CX JetSeries transparency film, the LX JetSeries transparency film, the LX JetSeries glossy paper, and the LX JetSeries single-matte inkjet polyester film. These special media are designed to give the best possible print quality for the printer system for which they were designed. In most cases, the media will operate over a range of products. The LX glossy paper and the LX transparency film both give optimum print quality performance on the HP PaintJet XL300, DeskJet 500C, DeskJet 550C, DeskJet 1200C, and DeskJet Portable printers. To ensure the highest possible print quality on all of these different printer platforms, various ink/printer/media interactions that occur while printing must be understood and accounted for in the printer, ink, and media design.

Polyester Substrates

Among the most common special media are the polyester-based materials. These include overhead transparency film, matte drafting film, and the bright white HP LX JetSeries glossy paper. All of these media are constructed on a base sheet made of biaxially oriented polyethylene terephthalate (PET).

Some of the factors that make polyester film a material of choice include its durability, thermal and hygroscopic stability, clarity, and stiffness. Along with all of these desirable attributes, a coated polyester substrate has several less-favorable properties that are not found in paper-based media, such as the base material's low absorptive capacity for aqueous inks.

Ink-Receptive Coating

The most obvious difference between paper-based materials and polyester film is that in a water-based ink system, the polyester film does not absorb any of the ink applied to the sheet. As shown in Fig. 1, the ink printed on the uncoated polyester sheet simply beads up on the surface. The identical pattern of ink applied to a coated polyester sheet retains the printed image.

The ink-receptive coating on the polyester film functions to absorb the ink, bind the free liquid of the ink vehicle until it can fully dry, cause the ink to spread into well-formed dots on the page, hold the colorant from the ink in place on the film, and provide outstanding image quality for both black and color. These are some of the properties that the development team will optimize during the design of any polyester film-based media.

Drying Time

The drying process on polyester film-based media is a two-fold mechanism, a combination of absorption by the ink-receptive coating and evaporation. The evaporation rate of the ink on a printed page can be estimated by printing the ink onto a sheet of an uncoated polyester film. With no ink-receptive coating on the film, all of the drying capacity must come from evaporative forces only. These forces are based on the surface area of the ink exposed to the air and the partial pressure of the ink vehicle.

When an uncoated polyester sheet is printed on a DeskJet 1200C printer and left to dry, an hour later it will still not be dry to the touch. This is because the nonvolatile components

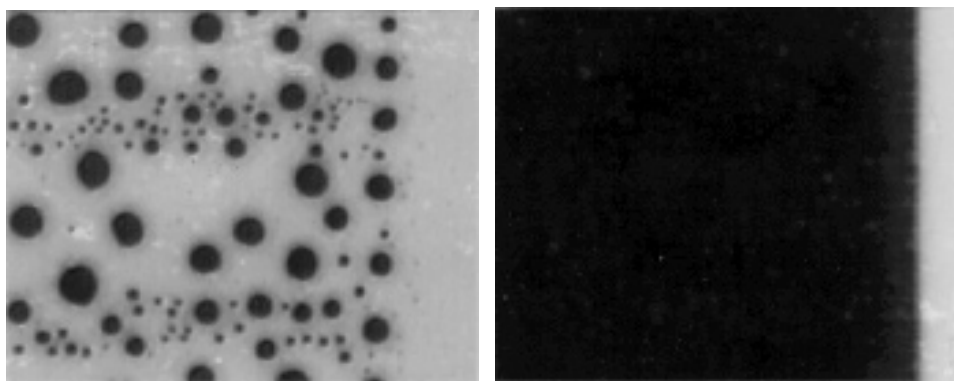


Fig. 1. Image printed on uncoated (left) and coated (right) polyester films.

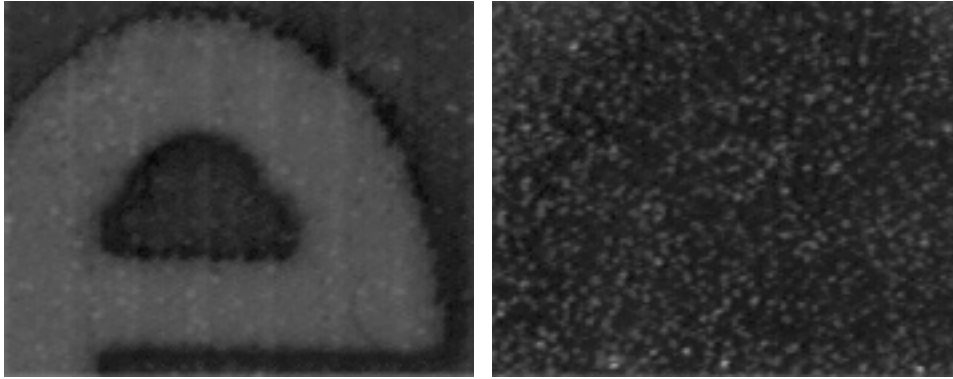


Fig. 2. Image printed on film with (left) and without (right) bleed fixing agents.

in the ink make the evaporative drying rate very low. By contrast, the ink applied to a coated sheet will be absorbed by the ink-receptive coating, and will be dry to the touch within a reasonable amount of time after printing. Achieving fast drying times while still maintaining the desired level of print quality is one of the most difficult aspects of polyester film development.

A typical inkjet printer will have a total ink flux applied to the sheet of approximately 30 to 40 g/m². The typical inkjet polyester film has an ink-receptive coating weight of 4 to 8 g/m². The ink-receptive coating must absorb and bind all of the ink applied to the sheet. While a greater amount of coating weight applied to the polyester base sheet would definitely improve the ability of the film coating to absorb the ink, additional problems develop such as image quality, curl, manufacturability of the film, and finished product cost.

Evaporation will eventually remove most of the excess volatile components of the ink. This will leave only the nonvolatile components from the ink to be absorbed by the coating. The inks used in the DeskJet 1200C have approximately 20 to 30 percent nonvolatile components. At full ink densities, there will be 6.9 to 9.2 g/m² of nonvolatile ink components remaining in the coating. Some of these nonvolatile components will act as humectants and hold additional moisture in the coating with them, making the total remaining mass of ink in the coating even higher. Depending on the environmental conditions, the humectant tendencies of the ink may also prevent the inks from fully drying on the film.

Bleed

Image bleed is another major development issue with polyester film-based media. The images shown in Fig. 2 depict two different ink-receptive coatings and two different levels of image bleed. The image coating without any bleed inhibitors shows a high level of bleed, allowing the colorant to diffuse through the coating medium freely. The film sample that does have bleed inhibitors incorporated in the coating retains the ink in the location where it was originally printed, making it a more robust printing system.

The ink-receptive coating is based upon combinations of water-absorptive polymers. These polymers act like highly viscous liquids on top of the polyester film. The viscosity of these liquids is very sensitive to dilution. As they absorb moisture either from a humid environment or from the ink printed on the sheet, the ink-receptive coating will act as if it has been diluted, and its viscosity will drop significantly. In

this less-viscous state, the colorants in the ink are able to diffuse more freely.

Colorant selection for the inks can have a significant impact on the ability of the ink-receptive coating to inhibit bleed. The size and mobility of colorants can range from molecular-sized dyes to large colorant particles that are orders of magnitude larger. A relatively small, easily mobile colorant particle will diffuse through the coating much more easily than a much larger colorant particle. Even the smallest, most mobile colorants can be immobilized somewhat by the use of a fixing agent in the coating. For example, large organic structures can bind the colorant, make the effective size of the colorant particle much larger, and make the colorant less mobile in the coating medium. Other fixing agents such as inorganic counterions dispersed within the coating will precipitate the colorants and make them less mobile in the coating medium.

Temperature also has a large effect on the bleed of an image on polyester films. This is evident if a sheet of polyester media is imaged at ambient conditions (23°C, 50% R.H.) and allowed to dry thoroughly. The imaged sheet can be placed into a moisture barrier such as a sheet-protector sleeve. If the imaged sheet in the sleeve is then moved to a high-temperature environment (35°C), the image will exhibit significantly more bleed than an identical image left at ambient conditions.

The effect of temperature is consistent with the Stokes-Einstein equation for liquid diffusivity:¹

$$D_{AB} = \frac{kT}{6\pi r \mu_B}$$

where D_{AB} is the diffusivity of the colorant A in the coating B, k is Boltzmann's constant, T is the absolute temperature in Kelvin, r is the effective hydrodynamic colorant particle radius, and μ_B is the viscosity of the coating. The observed effects of temperature, coating viscosity, and increased colorant particle size on the diffusivity of the coating are consistent with this relationship. Diffusivity is directly proportional to temperature and inversely proportional to the viscosity of the coating. Not so evident is an additional effect of temperature: the viscosity of the coating is strongly dependent on temperature. The viscosity of the coating can be estimated with the empirical Fox-Loshak correlation:²

$$\ln \mu_B = a + b/T(1+c)$$

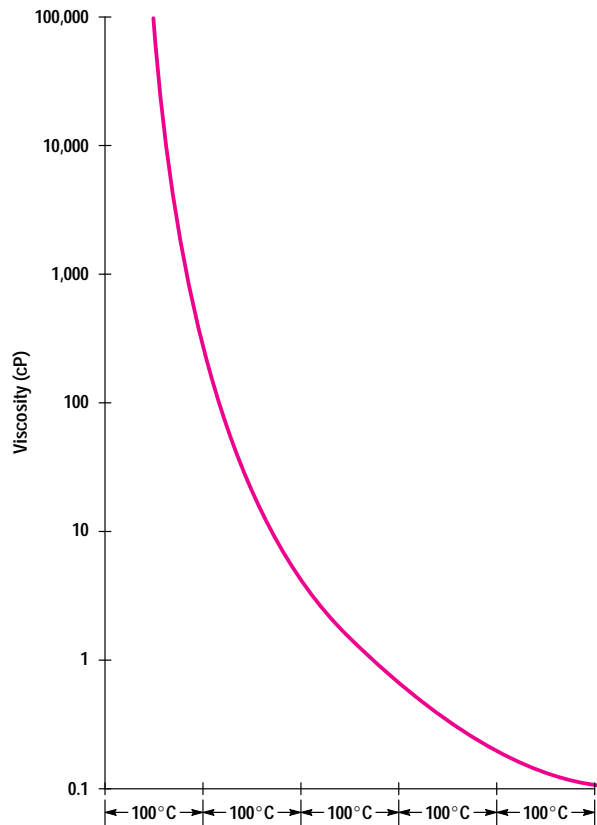


Fig. 3. Approximate temperature variation of liquid viscosity.³

where a, b, and c are physical constants (usually $c \approx 1$) for the particular polymers used in the coating. The chart in Fig. 3 shows the approximate relationship of temperature and liquid viscosity (in centipoise) for low temperatures (relative to the boiling point). The slope of the viscosity-temperature curve is very steep in the region of high-viscosity liquids ($> 10,000$ cP) like the polymers used in ink-receptive coatings. A small change in temperature of 12°C (from 23°C to 35°C) has a much larger effect on a high-viscosity liquid than on a low-viscosity liquid.

Dot Gain

On the other end of the spectrum from bleed is the issue of dot gain. In an effort to correct the problem of bleed, heavier coating weights or highly absorptive coatings are applied to the base film. The thicker or more absorptive coatings will significantly impact the ability of the ink to spread adequately

on the film, resulting in incomplete pattern fill and low image densities.

Fig. 4 shows the solid fill generated by a small-dot-size film coating. The optical density of the image printed with a small spot size (left) is 1.10, while the same area fill pattern with an optimized-dot-size film coating (right) has an optical density of 2.25. The ideal dot size for a dot matrix printer can be calculated based on the printer resolution. The ideal dot diameter in micrometers is:

$$\phi = 35921/R$$

where R is the printer resolution in dots per inch. This ideal dot size ensures that the dots in a field will have sufficient overlap to fill an area with 100% coverage. The ideal spot size for a 300-dpi printer is about 120 micrometers. As the dot density increases and approaches 100% area fill, the dots will interact with each other to generate a larger dot diameter than when measured as single dots. Therefore the dot size required to achieve complete fill is actually slightly smaller, and will vary depending on the dot growth of the individual coating.

The minimum dot size achievable for dithering purposes is directly related to the drop volume of the ink applied and the ink-to-film contact angle. Fig. 5 illustrates the effect of contact angle on the size of the spot generated with equal volumes of ink. The minimum image spot size is equal to the area of the ink drop in contact with the surface of the film. For a high contact angle ($\approx 90^\circ$) the minimum spot diameter can be calculated from the equation:

$$\phi = (6000V/\pi)^{1/3}$$

where V is the drop volume in picoliters. For a typical 300-dpi inkjet print cartridge that delivers around 100-picoliter drops, the minimum spot size would be about 58 micrometers, or about half the ideal dot size. Increasing the drop volume will increase the minimum dot size, making it closer to the ideal dot size. The problem with increasing the drop volume to increase the minimum dot size is that, because the relationship is cubic, a drop volume of 905 picoliters would be required to achieve the ideal dot size with no dot spread in the coating. This amount of ink would cause severe problems with drying time, blocking, and bleed, and would cause an uncounted number of problems on paper media.

This creates the dilemma of getting the drops to spread enough to form the ideal dot size without requiring large amounts of ink to do it. Compounding this problem are the

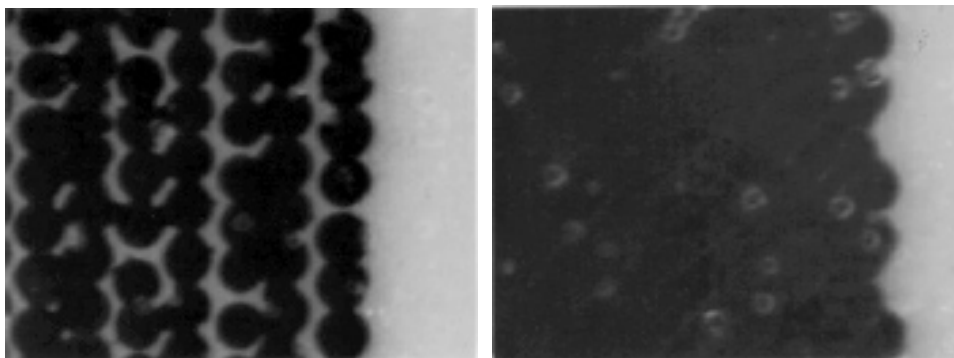


Fig. 4. Image printed with small spot size (left) and optimum spot size (right).

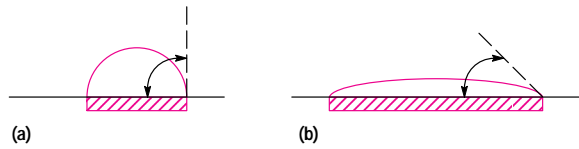


Fig. 5. Effect of contact angle on ink drop diameter on polyester media. (a) High contact angle (90°). (b) Low contact angle ($\approx 40^\circ$).

aspects of drying time and bleed. One method of generating dot spread is to promote ink spread through the coating. This will very often result in large amounts of bleed over time. The challenge is to design a coating that has enough dot spread to get sufficient ink coverage, and then have the spreading stop and stay fixed in place when the ideal dot size is achieved.

Even if the bleed can be controlled with very large dot spread, there are limits to the amount of dot spread that is desirable. If the dot size is too large, fine dithered patterns and individual dots can blend together. This has the effect of making a light gray scaled image blend together into solid, dark colors. The ability to halftone images is lost with very large dot sizes.

Blocking

The phenomenon of blocking is sometimes seen when an overhead transparency sheet is put into a sheet-protector sleeve. Blocking is defined as the localized sticking of the image to the sheet protector. Blocking will appear as blotchy areas on the image when projected. Overhead transparencies must be robust enough to survive storage in a sheet-protector sleeve. Sleeves are used by customers to protect the image from handling, or to facilitate storage in a binder. Most sleeves available on the market today are made of vapor-impermeable materials such as polyethylene, polypropylene, polyvinyl chloride, or polyester. The sleeves not only inhibit drying, but they also have a very smooth surface to promote clarity. If the ink on the coating is moist or tacky in any way, when the sheet is inserted into the sleeve the sleeve material will stick to sections of the imaged area of the transparency film and generate uneven blotchy patterns when projected.

To eliminate the blocking problem from a transparency system, there are several approaches that can be taken. The polymer coating on the film can be modified to be less tacky in the imaged areas, so the image will not stick to the sleeve. Coating composition and additives can be altered, but in many cases, other image properties such as bleed can or will be compromised.

Secondary top coatings can be applied to the film which will let the ink vehicle freely pass through to the bottom coating layer, which will absorb the ink and vehicle. This technique also may have adverse side effects of added drying time, image mottle, crystallization, or coating wrinkling.

Another method of improving the image blocking performance is to use mechanical spacers. Small particles can be dispersed in the coating that mechanically hold the sleeve away from intimate contact with the tacky film surface. The concentration and size of the particles used will depend on the extent of the tackiness of the coating used, and the physical appearance of the film. Small particles have a more

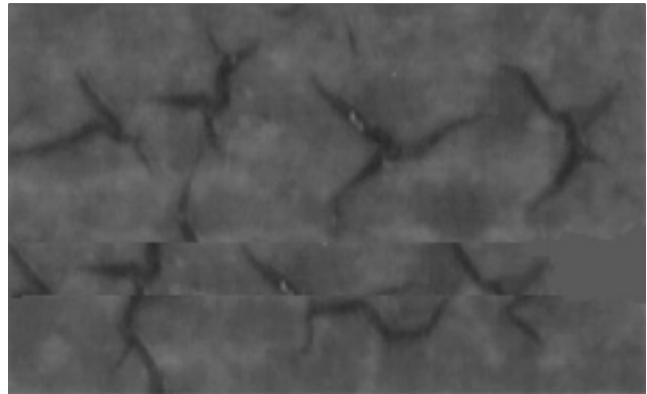


Fig. 6. Imaged film with wrinkles in the print area.

appealing texture on the film surface than do larger particles. Conversely, the small particles also need to be used in higher concentrations to be as effective as the larger particles. This will lead to higher levels of haze when the film is projected.

Wrinkling and Cracking

When the ink is absorbed, the coating will swell from the added volume of ink in the coating. This can add significant mechanical stresses to the coating layer as the ink/coating mixture dries. The swelled coating may be stretched to the point where it cannot recede back to its former dimensions. The resulting additional volume of the coating material forms folds and wrinkles in the imaged area. Fig. 6 shows an example of what wrinkling will do to an imaged area of film. The wrinkles will form darker lines in the imaged area. Not only does this generate severe print quality defects, but it also will impair the mechanical stability of the coating and allow it to peel off the base film. Many times, the wrinkling is on a much smaller scale than is visible to the naked eye, and simply appears as a high amount of haze in the imaged area.

Conversely, if the coating shrinks to a state much smaller than the original coating dimensions, cracks can appear in the imaged area as shown in Fig. 7. The addition of ink to the coating system can have several effects on the coating system. The ink vehicle can make the polymers in the coating less elastic, and the increased stresses from shrinkage will cause cracks in the imaged area. The ink may also change the amount of shrinkage that the polymers in the coating incur during drying, making

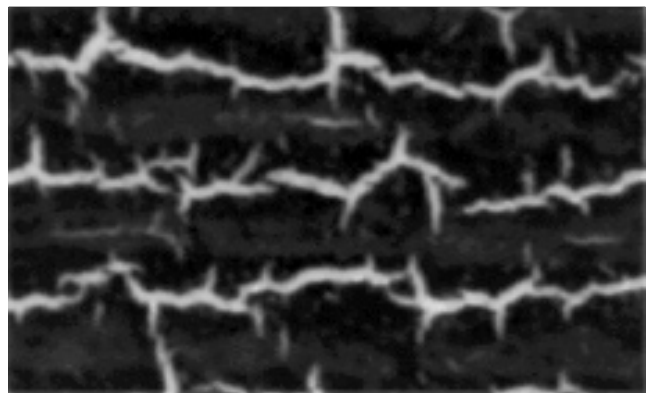


Fig. 7. Imaged film with cracked coating in the print area.

them shrink more than they can tolerate, which will also cause cracks to appear in the imaged areas.

Crystallization

One common problem associated with dye-based inks is that of dye crystallization. On a paper-based substrate, this phenomenon may never be noticed. It is best seen with transmitted light on an overhead projector. When printing on a coated polyester-based film, the dye molecules undergo a transition from a solvent system in the ink vehicle to a different solvent medium of the film coating. If the solubility of the dye in the coating solution is low, the dye can crystallize and generate undesired side effects. The crystallized dye will have a much higher light scattering effect than a dye that is not crystallized. The increased amount of light scattering will appear as haze on the projector. With several yellow dyes, for example, the crystallized dye will appear more brown when projected. The dye crystallization can be aggravated when fixing agents are used in the coating to reduce the amount of bleed.

Color Saturation

One of the main differences between paper printing and polyester film printing is in the end-use application. Images printed on paper or other opaque substrates are viewed directly with reflected light. In the case of transparency film, the images are almost always looked at with transmitted light and projected onto a white screen. The effect of the transmitted light and the magnification is that the image will tend to look more faded or washed out than the equivalent image printed on paper. To compensate for this, the print mode used in the printer to generate an image for transparency film uses more ink per unit area than for an equivalent image printed on paper. This can dramatically increase the drying time, the amount of bleed, blocking, wrinkling, cracking, and dye crystallization.

Heater Distortion

As printer speeds and resolutions have increased, heaters or dryers have been incorporated in the printer mechanism to speed the drying process and increase throughput. The problems faced by paper and film in an environment where printer-induced drying occurs are quite different. On an unheated paper sheet, the paper will want to swell and buckle when ink is applied. The heater in the product heats the paper and dries the ink quickly, preventing the ink from swelling the paper fibers.

In a polyester film-based product, the sheet will not cockle as a result of ink being applied, but it will cockle from distortion caused by the heater. The polyester base has a glass transition temperature of 73°C. When the film is heated above this point, the mechanical structure of the polyester is lost and the base film will wrinkle and warp. To avoid this, the printer does not heat an image printed on the transparency film as much as it does a paper image. The result is that the amount of ink drying is substantially less than the equivalent paper image. The additional ink required to solve the problem of color saturation on transparencies requires more ink to begin with, and the problems of drying time, bleed, and blocking are compounded.

Similar to the transparency film, the HP LX JetSeries glossy paper is also a polyester-based product. Instead of a clear

polyester base material, the HP LX JetSeries glossy paper has an opaque white polyester base sheet. The problem with the opaque white base sheet is the amount of heat that can be applied from the printer. The clear polyester base sheet absorbs very little infrared energy from the heater. Most of the heat energy is transmitted through the film and absorbed directly by the colored ink on the sheet. With the opaque white polyester sheet in the glossy paper, the base material absorbs all of the infrared energy from the heater, and the only heat energy that is absorbed by the ink on the page is from conductive heat transmission from the opaque white base sheet. The implication of this phenomenon is that the allowable heater setting for the opaque white polyester sheet is much lower than setting for even the clear polyester film. This makes drying time, bleed, and blocking even more of a problem for this base material.

Printer Mechanisms

Some of the considerations for compatibility with the printer mechanisms also put constraints on the polyester film-based media. Paper and polyester films have different mechanical handling problems and require different considerations in printer design. Polyester films need special adaptations or mechanisms that paper media do not need.

Scratches. Scratching is one of the most challenging aspects of handling polyester films in the media path of a printer. The smooth, clean surface of transparency films and the HP glossy paper will show scratches and scrapes from a poorly designed media path.

A simple burr on a piece of metal or plastic can put a scratch along the entire length of a sheet of film that will appear as a dark line when placed on an overhead projector, even in unimaged areas. A deep scratch can remove the ink-receptive coating from that area of film and leave a blank line through the image. A paper sheet will generally not show any print defects or material defects from these same conditions.

The media pick motion from the media tray can also leave scrapes on the image side of the film caused from the pressing force of the pick wheels during the sheet pick. On an overhead transparency, this can leave localized spots of high haze caused from minute scratches in the coating where the pick wheels make contact.

Sheet Feeding. Polyester film is often coated on only the image side, and the raw polyester is left on the back side. This can cause problems for both media pick and media advance accuracy. The uncoated polyester film is very smooth. When the printer attempts a media pick with a very smooth sheet, there can be a high frequency of missed picks or skewed sheets during the sheet feeding process. Having an uncoated back side of the polyester film can also induce media advance accuracy errors. If the film is too smooth, the main drive mechanism may not be able to advance the media without some degree of slippage. This will cause misregistration that leads to dark bands of overprinting in the imaged area. Many polyester films have a back side coating that may help these problems, but this only adds to the cost and complexity of manufacturing the film.

Curl. The method for holding down the media in the print zone also can affect the design of the polyester film-based

products. If the media is allowed to curl upward in the print zone, the printhead can crash into the media. The tear resistance of polyester films is well-known. Unlike paper, if the printhead crashes against the media, the polyester film will not tear, and may cause severe damage to the printhead or the printer itself. This very often will necessitate a back side coating on the film to balance the thermal and hygroscopic expansion of the image side coating. Similar to a thermostat, if a one-side-coated polyester film is heated or exposed to moisture, it will have differential rates of expansion and contraction that will cause the media to curl in one direction or the other. The back side coating is designed to match the front side coating for the degree of thermal and hygroscopic expansion so that the sheet will lie flat in all conditions.

The back side coating used for curl balance must also be designed to satisfy all of the other requirements for the print system. In the case of the transparency film, it must be clear, resist scratches, provide a good surface for sheet feeding, resist blocking to another imaged sheet, and perform its main function of providing curl control. In the case of the glossy paper, the back side coating must provide curl control and be resistant to image transfer when stacked on top of a previously imaged sheet. The back side coating must also have surface properties adequate for sheet feeding.

Pen and Ink Considerations

The ink is ultimately the only component that is added to the media to create the final image. Many of the ink-sensitive variables have already been discussed. Some of the other important considerations about the ink can have significant print quality consequences.

Colorants. Colorant selection is critical to the success of any media design project. The robustness of the colorants selected will greatly influence the media design. The tolerance to light exposure, the water solubility, the tendency towards dye crystallization, the pH sensitivity, and the color intensity of the colorants all have influences on the media design.

The amount of colorant loading in the ink also has similar contributions. A low colorant loading will require more ink to deliver the same amount of colorant to the sheet. Higher ink volumes create problems with drying time, bleed, and blocking. High dye loading allows for lower ink volumes, but the lower ink volumes increase the challenge of attaining high dot spread to generate the ideal dot size. The higher dye loading also increases the risk of dye crystallization.

The film coating must have a pH that is compatible with the colorants that are selected. There are some colorants that are stable in a low-pH environment, but they may lose their chromaticity in a basic environment. This would cause a base-sensitive colorant to fade prematurely if applied to a film coating that has a relatively high pH.

Inks. The physical properties of the ink must be carefully matched to the polyester film coatings to achieve a compatible printing system. The coating must have a surface tension that is compatible with the ink so that the ink does not bead up on the surface of the film, resulting in a mottled print image due to coalescence of the ink on the surface.

The film coating must also be compatible with the vehicle in the ink. The coating must be able to absorb the ink and

vehicle without dissolving in the ink vehicle. If the coating were soluble in the ink vehicle, heavy fill areas could dissolve the coating layer and disrupt the mechanical integrity of the film coating, making it very susceptible to scratching and smearing.

As mentioned earlier when discussing drying time, the percentage of nonvolatile components in the ink has a huge impact on the design of polyester films. If the ink does not eventually evaporate into the atmosphere, the coating must accommodate all of the remaining ink components. Since the total nonvolatile components in the ink can be equal to or greater than the total amount of coating, this is a major film design problem. The humectant aspect of the ink increases the total amount of ink that the coating must absorb. This is especially difficult when the printer system must operate in conditions of high temperature and high humidity. The amount of moisture in the air at ambient conditions (23°C, 50% R.H.) is about 60 grains per pound of dry air. At high temperature and high humidity (35°C, 80% R.H.) the amount of moisture in the air is about 220 grains per pound of dry air. This translates to a large increase in the amount of moisture contained in the film before any ink touches the page. The coating has a finite absorption capacity, and the more the coating is saturated with atmospheric moisture, the less ink it can absorb.

Multiple Product Compatibility

The customer viewpoint of polyester films is usually one of parity. One cannot look at a polyester film and determine if it is going to be compatible with a printer/ink system. The ideal polyester film solution is one that works on all HP ink-jet printers equally well. The number of printers and inks on the market today make this a nearly impossible challenge. There are printers such as the DeskJet 1200C with heaters incorporated in them to facilitate drying and promote high-quality, high-density images. There are also printers such as the DeskJet 550C that do not have a heater, but still produce stunning high-density black and color graphics. Each printer type has its own ink imaging system that places different demands on polyester film media.

Polyester film solutions that are designed to maximize the print quality for a highly water-based ink may not be able to satisfy the demands of an ink system that has a high level of nonvolatile components. If the ultimate print quality is to be maintained, the film designs must be tailored to match the printer/ink systems. Although the trend may be toward plain paper compatibility, that definitely does not apply to polyester film-based products. The cost of a single sheet of polyester film-based media requires that there be no compromises in the final output quality.

Conclusion

With the introduction of the HP DeskJet 1200C printer, plain paper printing in both black and color has reached new levels of quality. There is still an overall improvement that can be achieved by coupling the printer/ink system with a specially designed set of polyester films and coated paper such as the high-quality, high-density HP LX JetSeries transparency film or HP LX JetSeries glossy paper for high-quality photographic type imaging and presentation output. There will always be a demand for these media.

In the DeskJet 1200C system, the advances in the ink system that made high-quality plain paper color graphics possible presented a new set of challenges for the polyester film-based products. The high level of nonvolatile components in the ink made the already difficult task of controlling the drying time, bleed, and blocking on the film even more challenging. The requirement that this same film product also be backward-compatible with the existing HP 300-dpi inkjet printer family added to the design constraints.

Numerous challenges and design constraints must be addressed when developing any polyester-based film media. The technical achievement of the DeskJet 1200C polyester media set is the result of the teamwork and vision of several

teams dedicated to producing the highest-quality products. The DeskJet 1200C polyester film media set gives outstanding image quality on overhead transparencies and glossy paper not only on the DeskJet 1200C, but across all of the HP 300-dpi inkjet printer family.

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Inkjet Printer Print Quality Enhancement Techniques

Five print modes, each optimized for quality and throughput, HP Resolution Enhancement technology, heaters to dry the ink and the paper, and accurate print cartridge alignment and paper advance schemes contribute to the high print quality of the HP DeskJet 1200C printer.

by Corinna A.E. Hall, Aneesa R. Scandalis, Damon W. Broder, Shelley I. Moore, Reza Movaghar, W. Wistar Rhoads, and William H. Schwiebert

When the concept for the HP DeskJet 1200C printer was formulated, the design direction chosen was a text printer that also had excellent graphics performance. The initial decisions were fairly easy to make. For example, the printer was to be thermal inkjet with a resolution of 300 dots per inch (dpi). It was to be media independent (i.e., not just "special" media) and it was to have four print cartridges (black, cyan, magenta, and yellow) and most probably fast and high-quality printing options. To accomplish these objectives, the chosen printing system was a scanning carriage to hold the four print cartridges and a heated paper path to dry the ink quickly.

Having chosen a design path, each part of the writing system was investigated to determine how its contributions to print quality could be optimized. A dual approach was taken. Each print mode was designed to give the customer the best output in the least amount of time.

Improvements were made in various mechanical designs that optimize print quality in all print modes. While the DeskJet 1200C has five print mode options, those for transparency film and glossy media are not covered in this article. Print modes for plain paper (e.g., copier paper) are described briefly with an emphasis on optimizations that improve quality or throughput.

The mechanics and firmware that are common to all print modes were optimized with good overall print quality as the goal, and were also optimized specifically to improve known defects within a single print mode. The designs highlighted in this article are the main heater, the media preheater, the carriage encoder and print cartridge alignment scheme, and the paper advance accuracy.

Print Modes and Optimizations

Three plain paper print modes are available to the DeskJet 1200C user: fast, normal, and high-quality. Each print mode is capable of printing both text and graphics. While there are many subtle differences between the modes, the main differences are in the number of passes and the optical density of the black. The rate at which the ink can be dried is the main limit to throughput. Ink applied too fast will cause color bleed because of dye mixing at color boundaries, buckled paper from expansion of paper fibers, and mottled colors. Multipass printing can eliminate these defects by allowing

the ink to dry between passes. For example, a two-pass mode prints only half of the ink on the first pass and an additional scanning pass of the print cartridge is used to apply the rest of the ink. Multipass printing takes longer than single-pass printing, but quality is improved. Black optical density, especially in text, follows a similar pattern, trading off speed for quality. Applying more black ink to the same area and increasing the optical density requires more time to dry while improving quality.

Fast mode is just that—text speed is six pages per minute and graphics speed is under one minute per page. This speed is achieved by single-pass bidirectional printing, and consequently there are some of the defects listed above when printing high-density graphics in fast mode. Although text quality is still quite good, all 104 nozzles of the print cartridge are fired without regard to character splitting (i.e., a line of characters may be printed in two separate sweeps, top half first and bottom half second). While this mode is not recommended for high-density graphics, it will give the customer feedback about the colors chosen and the location and size of the graphics. Since this mode is heavily skewed towards speed and not quality, one way in which this mode was optimized was in the amount of time the heater is given to warm up the writing zone. Print quality is best when the writing zone is allowed to stabilize at the optimum temperature, but warm-up time requires the customer to wait. To avoid this wait, the printer will only warm up for the amount of time needed to receive the file. If the file is small the printer will begin printing almost immediately. The compromise works well for text and low-density graphics files.

The speed and print quality in fast mode are different from high-quality mode. Both text and graphics quality are improved in high-quality mode. Throughput is slightly reduced to four pages per minute for text and two minutes per page for graphics. Text is darker, and characters are not split and have smoother edges than text in fast mode. Through the use of a three-pass print mode, color-to-color boundaries are crisp and pass-to-pass paper advance errors are blended and distributed. Trade-offs made in this mode favored quality over throughput, although there are three notable exceptions. As mentioned above, three passes are used. Many numbers of passes were investigated, but when the improvement in quality (with more passes) was measured against print time,

the winner was three passes in terms of acceptable quality and speed. A similar decision was made with respect to slowing down a plot for very dense graphics. The longer the inked paper is over the heater, the more the ink dries between passes, reducing bleed and cockle. The printer is able to recognize dense graphics in a plot and slow the printing to allow for more drying. However when quality improvement and slowdown are compared, a point is reached when more slowdown gives only a small amount of quality improvement. For this reason, the slowdown equation has a hard-clip limit on the maximal time to print a plot.

The last example of how speed is maximized with minimum effect on quality involves how black is printed. High-quality text has the scan-axis resolution enhanced from 300 to 600 dpi as described below. Since the printer may not always know when a plot has changed from text to graphics, it is necessary to print all black in this 600-by-300-dpi format when using high-quality mode. Printing at 300 dpi in the scan axis takes all of the available firing windows, so the printer cannot print 600-dpi black and other colors in the same swath unless the carriage halves its speed or a separate swath for black is used. Both options severely degrade throughput. However, as detailed below, the position of the carriage and thus the position of the drops in the carriage scan axis are well-characterized on the DeskJet 1200C. Harnessing this accuracy is the key to being able to print black on the scan that would normally be the carriage return (retrace). Throughput is good, since no time is lost in a carriage return. Good dot alignment in both directions allows all the color to be printed on the forward pass and black to be printed on the retrace while the carriage is traveling at almost two-thirds the usual carriage return velocity.

Normal mode is the third plain paper print mode option. Color printing is identical in normal and high-quality modes. Normal mode text is printed with the same resolution as fast mode: 300 dpi. Text printed in normal mode will always have white space between swaths as in high-quality mode. In this mode, a customer can have full-quality graphics with nearly the text speed of fast mode (six pages per minute). Additionally, because 300-dpi dots appear smaller than 600-dpi dots, this mode works well for images where small dots reduce the overall grainy appearance of the print. Because this mode is a mixture of fast and high-quality modes, during the development of the printer the quality and throughput of normal mode were both subject to modification to achieve the best mix. For example, the initial implementation of normal mode printed all black text and black graphics (anything other than text is considered graphics) in one pass, that is, all nozzles ready to fire. This worked well for spreadsheets, but not so well for images and business graphics. To improve the quality, all black-only graphics are printed in three passes to maintain superior quality. The trade-off for quality was worth the longer printing time.

Resolution-Enhanced Text

HP Resolution Enhancement technology (RET) is a technique used to improve text quality by increasing the effective resolution of an image and selectively placing or deleting dots to improve the overall smoothness of the character. Used on inkjet printers, RET increases the effective resolution from 300 by 300 dpi to 600 by 300 dpi. The edges are smoothed by

applying rules that are triggered by the detection of a specific pattern of dots.

The following considerations influenced the design of the inkjet implementation of RET. First, enhancement via RET should never degrade and in most cases should improve text quality. Second, the inkjet implementation of RET had to conform to the low-cost goals of the printer. This limitation directly impacts the size of the rule set, since the rules are embedded in the ASIC (application-specific integrated circuit). Finally, the implementation must not impact printer throughput.

With these considerations in mind the primary goal of any implementation of RET is to "smooth the jaggies" inherent in any discrete dot placement technology by effectively increasing the resolution without actually transporting the data twice. While achieving smoother lines, the stroke density and weight must be preserved. These goals are accomplished by defining a specific rule set that fits within the cost constraints of the hardware. These constraints force the inkjet implementation of RET to target the most apparent causes of poor text quality and to limit the rule set accordingly.

Other limitations of the inkjet implementation of RET are the small size of the pattern recognition window and the possibility of enhancement only along one axis. The size of the pattern recognition window allows most characters to be improved; however, patterns not recognizable within the limited window size will not be enhanced. The inkjet implementation of RET enhances near-vertical edges of text in portrait orientation. Characters in landscape orientation will not improve as much, since most character edges when oriented for reading are near-vertical.

RET was first implemented on the HP LaserJet Series III printers. The inkjet implementation of RET is significantly different in several respects. The most significant is that the LaserJet printers are capable of controlling both dot timing and intensity. This allows the LaserJet printers to enhance both vertical and horizontal edges. Also, on the LaserJets the RET function has its own dedicated ASIC whereas the inkjet implementation fits RET onto the print-engine ASIC. The inkjet rule set was determined statistically by testing the LaserJet rule set and using only those rules that occurred a significant number of times per page.

Each RET rule consists of two parts: a pattern and an action. When the pattern is recognized the associated action is performed. The action consists of setting or clearing a bit or a set of bits. Fig. 1a depicts a pattern detected within the unenhanced image. Fig. 1b depicts a possible action associated with the pattern in Fig. 1a. Fig. 1c shows a possible unenhanced portion of an image containing the pattern shown in Fig. 1a. Fig. 1d shows the result of applying the rule to the original image.

The edge smoothing effects of RET are easily seen in the photomicrographs of Fig. 2.

Mechanical Improvements

Within each print mode, a variety of writing system designs affect print quality. The effect of the main heater is enormous. It is located directly below the print zone (see Fig. 3) and functions to dry the ink quickly. It prevents objectionable

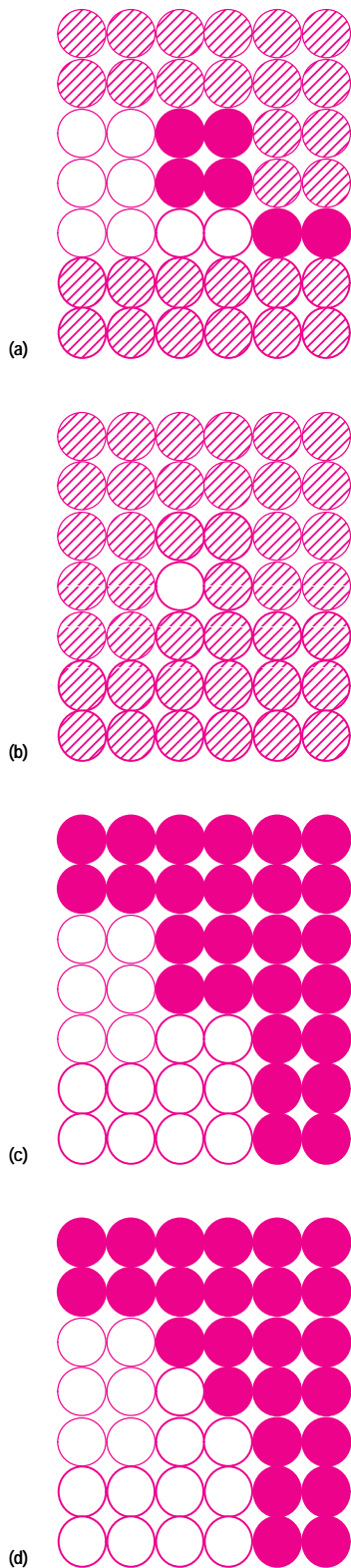


Fig. 1. (a) A pattern detected within an unenhanced image. The striped circles represent pixels that can be on or off (“don’t care”). Empty circles represent pixels that are off and solid circles represent pixels that are on. (b) A possible action or rule associated with the pattern in (a). The striped circles represent pixels that will not be changed. Empty circles represent pixels that will be changed from on to off. Solid circles represent pixels that will be changed from off to on. (c) A possible unenhanced portion of an image containing the pattern shown in (a). (d) The result of applying the rule to the original image.

bleed and paper cockle (out of the plane puckering of the paper caused by the aqueous nature of the ink) while increasing throughput.

The heater consists of a wire element which, when heated, radiates in the 3-to-5-micrometer range. This is the optimum range to excite and evaporate water molecules. The element is suspended in a quartz tube which is housed in a three-sided reflector which directs the radiation to the printing area. When the ink is dried quickly, the water does not have a chance to swell the paper fibers and produce cockle, nor to mix with an adjacent wet drop of ink and produce bleed.

If there is a data interruption or an I/O delay, the heat from the main heater runs the risk of discoloring (browning) the paper or causing a hue shift when a given swath of printing is dried for longer than the previous or succeeding swaths. To prevent these objectionable print quality errors, the printer constantly monitors the data buffers, and as soon as it sees the data rate slowing down, the printer begins to ramp down the print speed and turns off the heater. In this way, the hue shift is hidden by making it appear more gradual, and browning is prevented by reducing the heat. The reduction in throughput coupled with the reduction in heat maintains the print quality and does not adversely effect bleed or cockle.

One of the challenges of printing in a heated writing system is paper shrinkage. If paper is allowed to enter the heated print zone without being preconditioned, the paper will shrink during printing. In single-pass printing this shrinkage shows up at the swath boundaries as a misregistration. For example, a vertical line placed near the edge of the media will look like stairsteps. In multipass printing, the errors will show up as individual misregistration of dots. In an area fill, this appears as a white haze. Different environmental conditions and different media types will affect the amount of error that occurs. Humid conditions and heavy bond papers will produce the worst errors.

The DeskJet 1200C preheater is designed to precondition paper evenly before it enters the print zone. The heater consists of a flexible polyimide laminate with etched copper traces. The power is regulated by the resistance of the preheater itself, which eliminates any cost of supplying a pulse width modulated or other regulated voltage. If the preheater is cold when the printer receives a print job, the cold preheater draws approximately 45 watts. As the copper traces become hot and the resistance builds, the preheater consumes a much lower steady-state power.

One of the design criteria considered during development was warm-up time. By using a thin laminate (less than 0.010 inch) and suspending the preheater away from any large thermal masses, the warm-up time is reduced to less than four seconds. This is less than the time required to feed a sheet of paper and start printing. In this way, the time spent preconditioning the media is free and throughput for the customer is unaffected.

While the preheater minimizes the adverse effects of media shrinkage on dot placement, other factors that greatly affect dot-to-dot alignment are the accuracy with which the media is advanced, the control of the carriage scanning velocity, and the success of the carriage in reliably aligning four print cartridges.

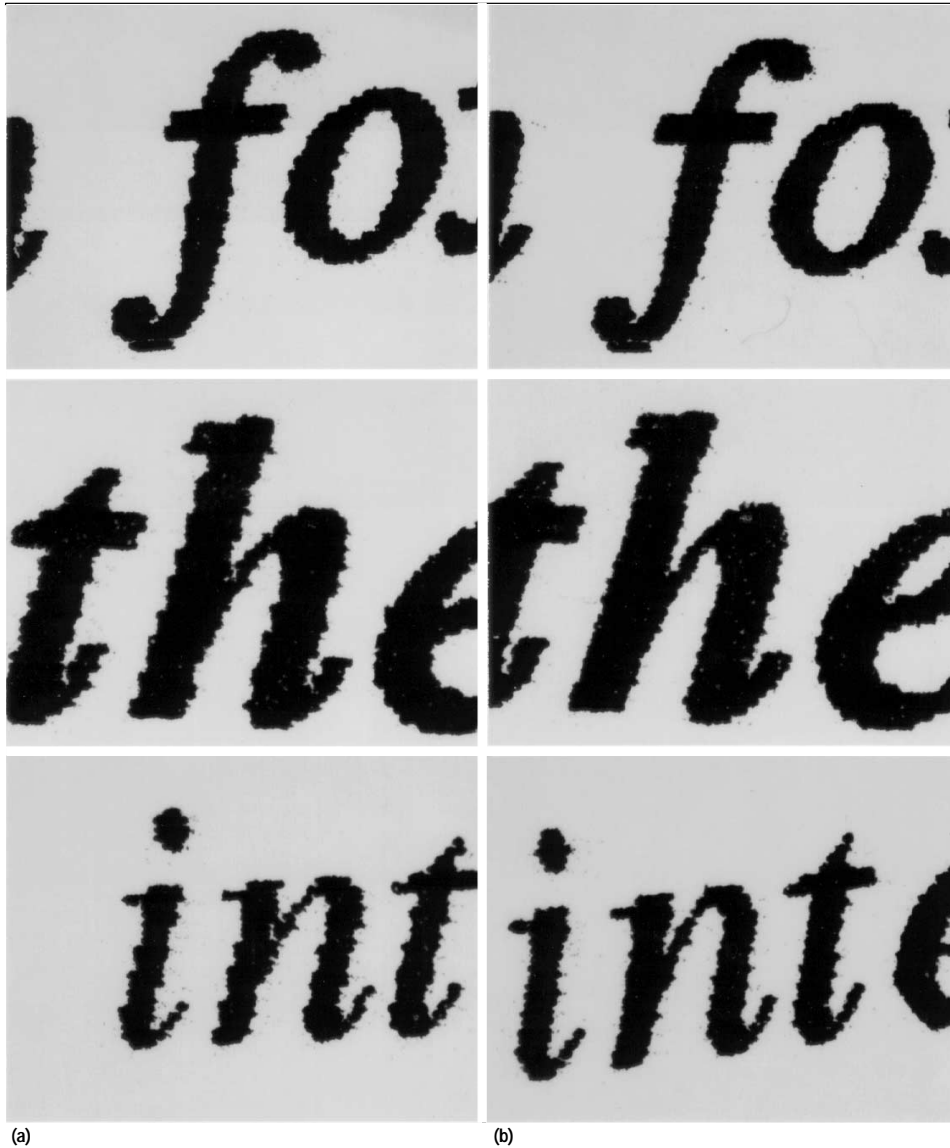


Fig. 2. Examples of the edge smoothing effects of HP Resolution Enhancement technology (RET). (a) Unenhanced text characters. (b) The characters in (a) after the application of RET.

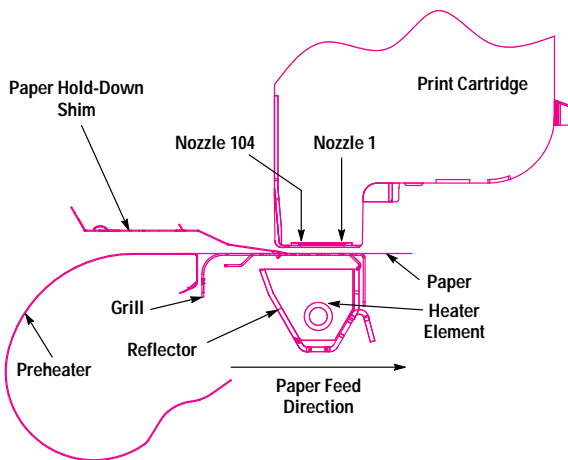


Fig. 3. HP DeskJet 1200C printer writing system.

Carriage Position

The position of the carriage as it scans the paper is controlled by a linear encoder with a resolution of 150 lines per inch. Servo control of the carriage is based on the quadrature output (4×150 counts) of the carriage-mounted optical encoder and is updated every 0.002 second. The velocity is maintained by real position and estimated velocity feedback. Firing pulses are generated by an extrapolator from the rising edge of a single channel of the encoder. This eliminates the optical errors between encoder channels. These artificially generated pulses are much more accurate for dot placement than the encoder quadrature output, which relies on optical and analog measures.

As mentioned in the print mode descriptions, accurate dot placement is crucial when printing bidirectionally. Errors show up as small horizontal offsets (in the range of 0.001 to 0.004 inch) when a line is printed vertically down the page. Because the velocity is well-controlled by means of the encoder, the firmware can repeatedly compensate for the drop trajectory in either scan direction.

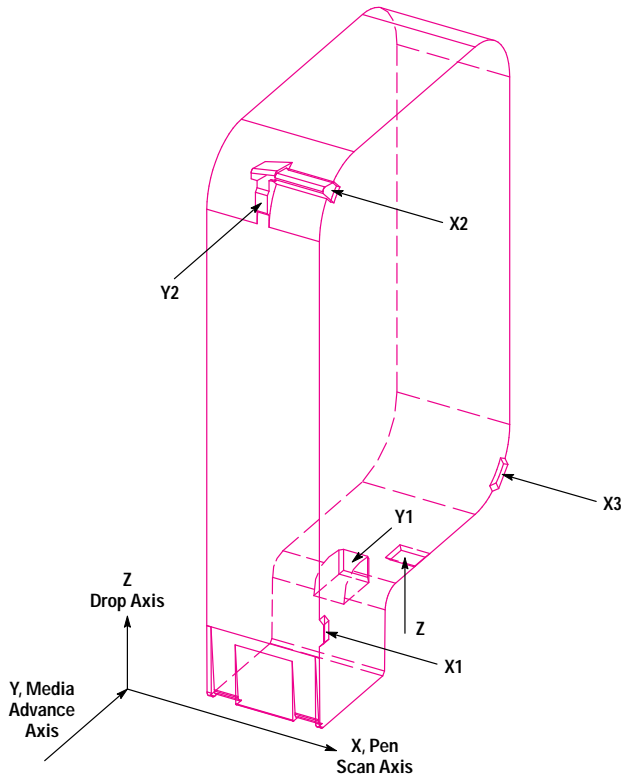


Fig. 4. HP DeskJet 1200C print cartridge datums.

The dynamic rotation about the Z axis (perpendicular to the media) and chatter effects of the carriage in unidirectional and bidirectional printing are minimized through the use of a preloaded bushing and spring that bias the carriage against the slider rod on which the carriage rides.

Print Cartridge Alignment

Another critical factor in attaining high-accuracy dot-to-dot alignment in a four-print-cartridge printer is the alignment between the print cartridges. For practical purposes, the alignment of the print cartridges is defined by three tolerances: the tolerance of positioning the print cartridges in the X or carriage axis and the Y or media axis, and the angular tolerance about the Z axis, which is normal to the media surface (see Fig. 4). The angular tolerance is required to keep vertical lines from having a jagged appearance. These tolerances must be kept as small as possible while taking into consideration the need to keep the carriage and printer small, easy to use, and inexpensive.

Several possible solutions to the problem of attaining accurate print-cartridge-to-print-cartridge alignment were investigated. One idea was to develop a part design and molding process that could hold the required tolerances. This was considered risky, and the mechanical architecture that was developing did not appear to lend itself to this approach. A second concept was to use a test plot and front-panel controls to allow the user to tell the printer how much to move each color plane to achieve good dot-to-dot alignment. This option would have worked well to provide a high-quality printing solution, but it was felt that it required too much customer interaction. Also considered was a mechanical

adjustment of the print cartridge position to attain the desired alignment. This system would allow near perfect alignment, but would tend to be bulky, complex, expensive, and possibly, again require more of the customer than desired.

The selected solution is to machine three of the six points of contact (datums) on both the print cartridge and the carriage. Three of the datums are far away from the printhead (X2, Y2, Z), so their position can vary as much as normal molding tolerances without introducing significant print-cartridge-to-print-cartridge alignment error. The remaining three datums on the print cartridge carriage are located so that they can be easily machined (X1, X3, Y1). The three machined datums are located such that two of them are close to the printhead (X1, Y1) and one is much farther from the printhead (X3). The two datums near the printhead (X1, Y1) control the alignment in the carriage and media axes. The datum farther from the printhead (X3) works with the print cartridge axis datum near the printhead (X1) to control the angle of the printhead such that the column of nozzles on the printhead is parallel to the media advance axis. Biasing springs press the print cartridge against the datums. The combination of the datum locations selected and the machining of the print cartridge and carriage datums provides a simple, inexpensive way of attaining tight alignment tolerances between the print cartridges. The system is open-loop, yet reliable and requires no customer interaction.

Paper Advance

An analysis of the contributions to print quality from various mechanical designs within the printer would be incomplete without an exploration of the paper advance system. This system was given heavy focus throughout the DeskJet 1200C development because advance accuracy is such a large component of dot placement and poor advance accuracy produces the very visible error called banding.

The paper advance mechanism in the DeskJet 1200C consists of a stepper motor, a helical pinion, a helical drive gear, and a drive shaft with two drive wheels to push the media. The system is designed to make 32-nozzle moves for three-pass color graphics printing and 104-nozzle moves for text printing. In three-pass printing, the dot-to-dot error in the paper direction is accumulated during each of three 32-nozzle moves. Therefore, the paper advance error between 32-, 64-, and 96-nozzle advances controls the banding errors associated with paper advance. To minimize the contribution of the 96-nozzle advance error (potentially the greatest because some of the errors tend to be grow linearly with advance distance), the gear train is designed to turn the stepper motor and its pinion through one revolution during a 96-nozzle move. Thus the pinion and stepper errors are virtually zeroed out each rotation. This design reduces the 96-nozzle error to the same value as the 64-nozzle error, which greatly improves print quality.

The DeskJet 1200C paper advance mechanism is not only designed to provide very accurate paper placement, but also to be manufacturable in a high-volume environment. To meet both goals, a mathematical model (Monte Carlo method) of the drive system was developed. The model simulates the movement of all components in the paper drive

system from the stepper motor and its pinion to the drive gear and shaft. The inputs to the model are component tolerances and other environmental variations that affect drive accuracy; the output is paper advance error. After the validity of the mathematical model was confirmed, the proven model demonstrated that as long as the drive components stay within their specified tolerances, the paper advance will be within specifications as well. These components are produced with at least one standard deviation of process margin, so the resulting paper advance also has process margin. This means that the accuracy of most swath advances is better than the goal.

Throughout the development of the DeskJet 1200C, print quality was one of the main outputs of printer testing, not only at ambient, but also at selected extreme environmental conditions. When print modes or mechanical designs needed

to change, other considerations beyond print quality, such as user friendliness and high-volume manufacturing, were factored into the scope of the changes. Compromise was necessary in all decisions, and yet clear understandings of what each print mode was expected to deliver and the magnitude of a design's effect on print quality kept the printer from becoming too "clever" (i.e., complicated) and provided a design that can truly fit into the mainstream office.

Acknowledgments

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The Third-Generation HP Thermal InkJet Printhead

The monolithic integration of driver transistors with the thermal inkjet heater resistors leads to vastly improved performance with reduced cost per page for the customer.

by J. Stephen Aden, Jaime H. Bohórquez, Douglas M. Collins, M. Douglas Crook, André García, and Ulrich E. Hess

For the third generation of HP thermal inkjet printers, three parameters were selected for significant improvement: print quality, print speed, and cost per printed page. Elsewhere in this issue, print quality and cost per page improvements are discussed. This article describes a printhead designed for the new HP DeskJet 1200C printer that permits a significant increase in the print swath with a corresponding increase in print speed.

Increasing print swath means more nozzles on the printhead from which to fire ink, hence a larger number of heater resistors. The printhead used in the current family of DeskJet printers (for example, the DeskJet 550C) has 50 nozzles and 50 corresponding heater resistors. The new printhead described here has 104 nozzles with 104 corresponding heater resistors. The direct drive technology used in the 50-nozzle printhead requires 54 interconnections between the printhead and the printer. A 104-nozzle printhead fabricated using the same direct drive technology would have some 112 interconnections between the printhead and the printer. By more than doubling the number of interconnections, the interconnect reliability would be compromised. Also, the size of the silicon chip would then be determined by the number of contact pads and would become uneconomically large.

Since a silicon chip is used to carry the passive thermal inkjet heater circuitry, simple MOS transistor drive circuitry was incorporated on the same substrate for the new 104-nozzle printhead. The name "integrated driver printhead" has been given to this combination. This integration reduces the number of interconnections required and thus the number of contact pads required on the integrated driver printhead.

Simplified direct drive and integrated drive circuits for a 20-nozzle printhead are compared in Fig. 1. These conceptual circuits can easily be extended to 104-nozzle printheads. Table I compares the various characteristics of the DeskJet 500C and DeskJet 1200C printheads. The 104-nozzle DeskJet 1200C printhead has only 36 interconnect pads whereas the direct drive 50-nozzle DeskJet 500C printhead has 54 interconnect pads. In spite of the larger print swath of the DeskJet 1200C printhead, its silicon chip size is comparable to that of the DeskJet 500C printhead and is significantly smaller than it would be if direct drive technology were used. Despite the increased complexity in using integrated drivers, the smaller silicon chip size leads to a lower cost per printhead than would be obtained with a direct

drive printhead having the same print swath. This translates to a lower cost per page for the customer. In addition, the firing chamber geometry and the ink properties of the DeskJet 1200C printhead are optimized to increase the operating frequency (i.e., the number of ink drops fired per second). These improvements are discussed elsewhere in this issue.

Table I
Printhead Characteristics

| | HP DeskJet 500C Printhead | HP DeskJet 1200C Printhead |
|----------------------------|------------------------------|-------------------------------|
| Number of Nozzles | 50 | 104 |
| Number of Heater Resistors | 50 | 104 |
| Resolution (dpi) | 300 | 300 by 600 |
| Print Swath (in) | 1/6 | 1/3 |
| Number of Pads | 54 | 36 |
| Chip Size (mm × mm) | 5.44 × 7.66 | 4.2 × 12.2 |

Demanding Environment

The integrated driver printhead is immersed in ink. The black ink is a pigmented ink with anionic dispersants. The color inks are based on anionic (sulfonated) dyes. The inks also contain sodium, chlorine, and potassium. It is well-known that mobile sodium ions in the oxide layer of an MOS device can modify the threshold voltage and thereby destroy the device.¹ Because of the close proximity of the ink to the active devices and the elevated temperature during operation, ionic contamination was identified during the process selection stages of the integrated driver head development as a potential problem with an MOS integrated driver head. The inks also contain solvents that have been shown to cause failure in the mechanical components of thermal inkjet printheads. The new integrated driver head thin-film structure had to be proven insensitive to both of these potential problems. Life test and soak tests combined with device characterization were performed throughout the development whenever significant thin-film process or ink changes were made. Ionic contamination never surfaced as a problem—threshold voltages were always found to be stable with respect to ink exposure. However, tests proved to be valuable because they helped identify thin-film deposition process

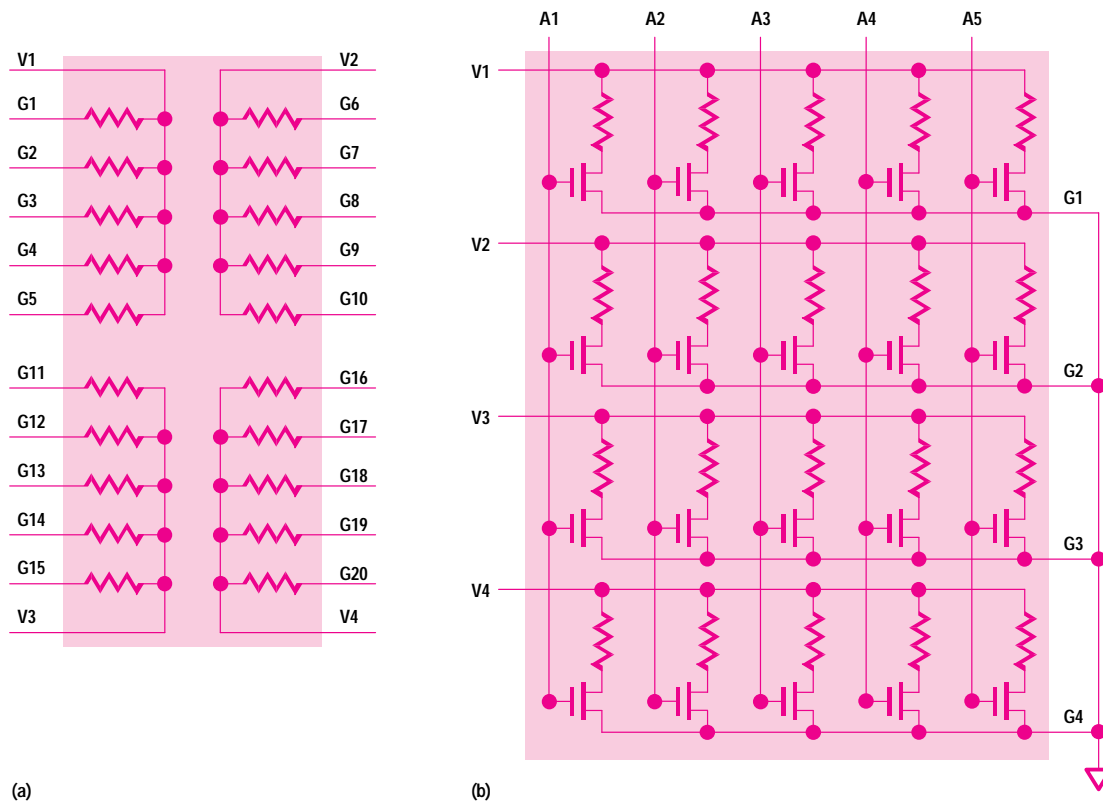


Fig. 1. Simplified drive circuits for a 20-nozzle printhead. (a) Direct drive, 24 lines. (b) Integrated driver printhead, 13 lines.

and materials combinations that produced the best film adhesion in the hot ink environment.

Thermal Cycling and Mechanical Cavitation

The thin-film heater resistors used in the integrated driver printhead are subjected to severe mechanical stresses during operation. These stresses arise from thermal cycling of the resistors and cavitation forces as the vapor bubbles collapse on various surfaces within the firing chambers. The thin-film resistor material is heated from near ambient temperature to well above the superheat temperature of water (the principal solvent in HP thermal inkjet inks) within several microseconds by each firing pulse. This results in large cyclic temperature gradients within the thin-film stack, in both the vertical and lateral directions. Thermal cycling to this extent creates extremely large mechanical stresses and therefore imposes a number of constraints on the thin-film materials used. In addition to chemical compatibility and thermal stability, the films above and below the resistor film must have stable, well-matched, film stresses to prevent cracking or delamination during operation.

During the cooling phase of each drop ejection cycle, the drive bubble collapses, allowing refill of the firing chamber with ink. While seemingly benign, the bubble collapse can create a microjet of fluid which causes large localized pressures on the surface it impacts. This process, known as cavitation, is difficult to observe directly, but it does produce pressures in excess of 130 atmospheres. If the firing chamber is incorrectly configured, these cavitation events can peen the protective films over the resistor and actually chip away portions of the film. Once damaged, the nucleation of subsequent bubbles is altered. If severe enough, this damage

initiates a chain of events that can cause the resistor to break open and fail (see Fig. 2).

These mechanical stresses, which are unique to thermal inkjet technology, impose constraints on the integrated circuit chip in the integrated driver printhead, since the drive transistors share several films with the thermal inkjet portion of the device. The tantalum cavitation barrier is used as part of the metal interconnect. The dielectric passivation films that protect the firing resistors also protect the drive transistors and serve as the dielectric between the first-level and second-level metals. The resistor underlayer film, composed of SiO₂, also serves as the field isolation oxide in the NMOS drive transistors. Any film parameter adjusted to optimize the transistors is therefore likely to impact the thermal inkjet performance and vice versa. The resulting web of interactive variables complicates both the design and the process development.

High Current and Voltage

The pulses of electric energy delivered to the heater resistors to fire drops of ink are very small—they are measured in microjoules. However, the pulse of energy must be delivered in a very short amount of time for reasons of drop ejection performance and printer throughput. Because the ink-drop ejection rate is very high and because of the time it takes to demultiplex the firing pulses, only a small window of time is available for the firing of each drop. Since the pulse energy must be delivered in a period of several microseconds, the current flowing through the transistor when it is on is moderately high and the voltage across a transistor when it is off is also moderately high. The needs for high currents and voltages and small devices are in conflict. Thus, a significant

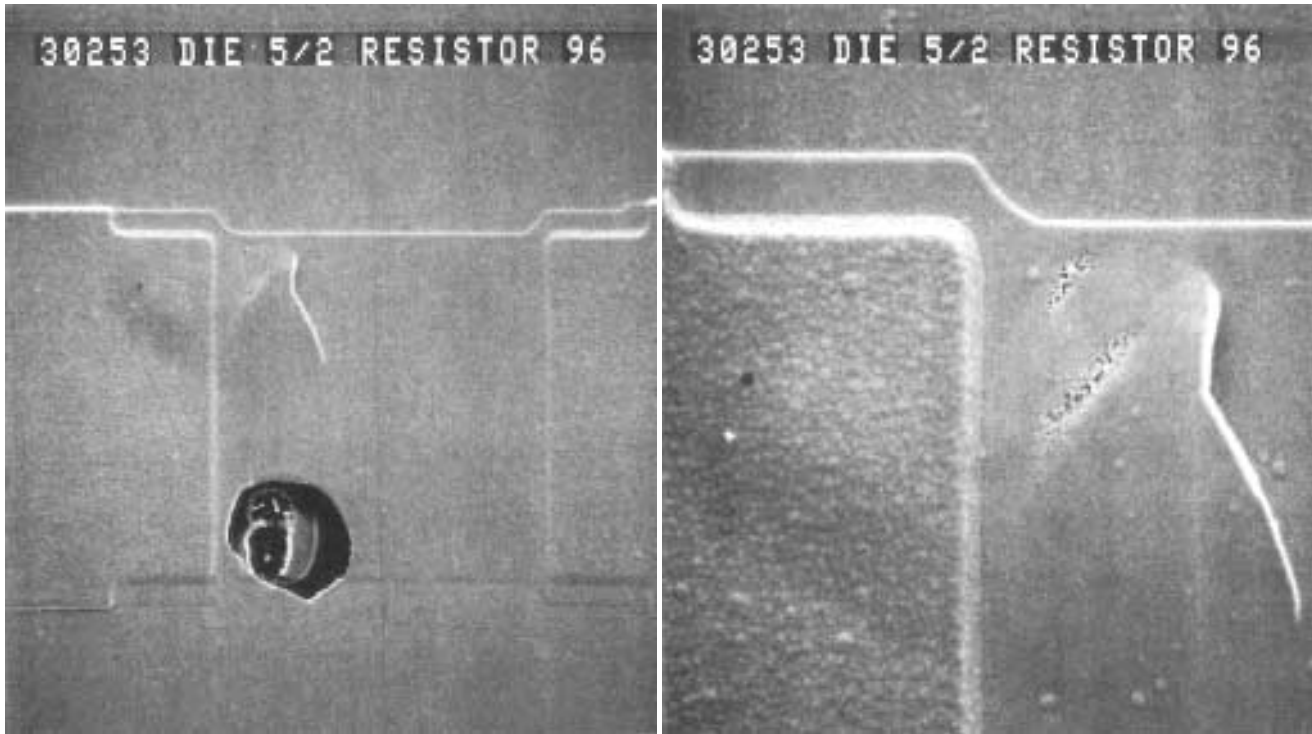


Fig. 2. Scanning electron micrographs of cavitation damaged resistors.

effort was required to select the process parameters and design rules for the new integrated driver printhead.

Electrostatic Discharge

The integrated driver printhead must be robust to electrostatic discharge (ESD) events. This requirement is a result of the unusual packaging of this type of device. The end user will need to replace the inkjet cartridge after the ink supply is exhausted. This type of handling, by printer users not necessarily familiar with ESD effects and precautions, potentially exposes the contacts on the print cartridge interconnect circuit to a variety of uncontrolled ESD events. This was addressed using a field plate diode ESD protection circuit to protect each ungrounded input pad.

Low-Cost, High-Yield, High-Volume Manufacturing

Perhaps the most fundamental constraints on the development of the integrated driver printhead are those imposed by commodity manufacturing. Since the print cartridges are user-replaceable, they must be manufactured in large volumes at low cost to support a continually growing installed base of printers, in addition to the units shipped with new printers. This approach requires very high-yielding, simple processing with a minimum number of process steps. Cost and simplicity assume relatively greater importance in trade-offs with features and device performance than is typical for traditional IC processes.

Integrated Circuit Technology

The need for the driver circuitry and the thermal inkjet thin-film network to be electrically connected to each other on the same substrate presented a choice of switching transistor options (IC technologies such as bipolar, NMOS, etc.) as well as ways of combining or perhaps hybridizing the IC and thermal inkjet technologies. Since the second generation of

thermal inkjet technology used an oxidized silicon substrate, it was decided that a monolithically integrated driver transistor and heater resistor circuit would be optimum. Because these printheads are replaced when the ink is depleted, it is important to use the lowest-cost process that will meet the printhead performance goals. Thus, a lower-cost three-mask NMOS process was selected over a five-mask bipolar process.

Several options were considered for the resistor addressing circuitry. The three most promising were row-column demultiplexing (demux), blocking diodes, and a proprietary passive enhanced multiplexing scheme. The row-column scheme was chosen and is shown in Figs. 1b and 3. This scheme reduces the number of pads from N to $2\sqrt{N}$ for a printhead with N resistors. Thus, the simplest 104-resistor printhead would require 21 pads. Additional ground and test pads raise the actual total on the DeskJet 1200C printhead to 36 pads.

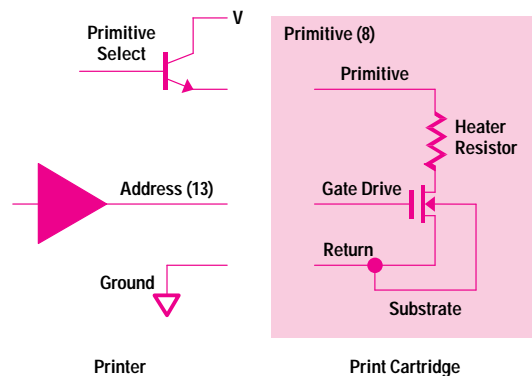


Fig. 3. Printer/printhead interface.

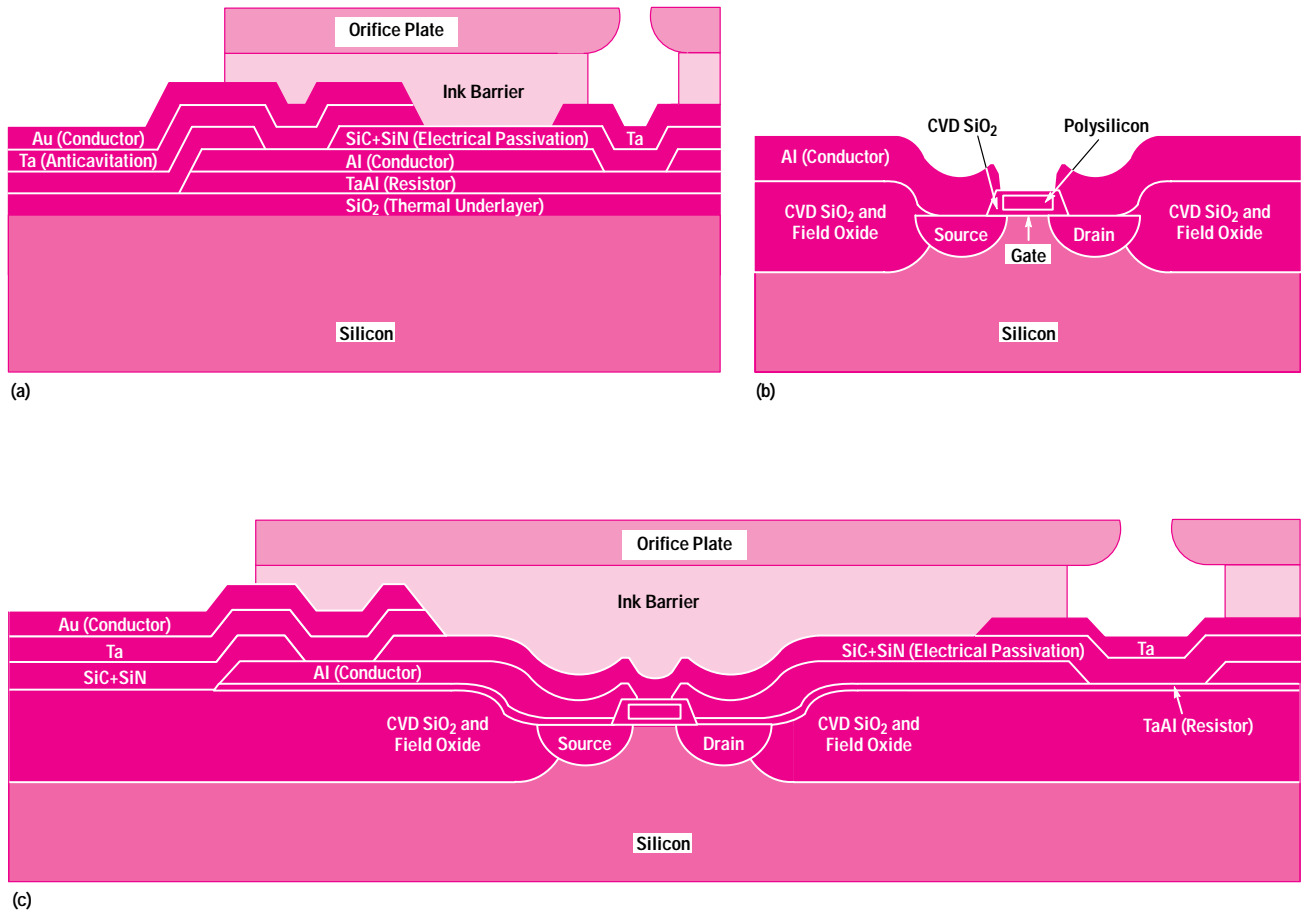


Fig. 4. (a) Thermal inkjet, (b) NMOS, and (c) merged technologies.

Process Implementation

From an IC process engineer's point of view, the existing thermal inkjet process (Fig. 4a) can be thought of as a special double-level metal interconnect process with an unusual interlevel dielectric, namely the $\text{SiN}_x/\text{SiC}_y$ thermal inkjet passivation, and an upper interconnect level consisting of a thick refractory glue layer and a thinner noble bonding layer. If the first-level thermal inkjet conductor could also serve as the IC contacting metallization, and if the IC interlevel dielectric (see Fig. 4b) could be part of the thermal inkjet oxide underlayer, an elegantly simple process could be achieved. The resulting merged NMOS and thermal inkjet structure is shown in Fig. 4c.

To achieve this simplicity, it was necessary to draw on the strengths and flexibilities of both the IC and thermal inkjet technologies. Except that typical field oxides in NMOS technology are significantly thinner than the thermal isolation oxide required in thermal inkjet technology, these films are quite comparable. Thus, a thicker thermal oxide can serve both the thermal inkjet and NMOS requirements. However, NMOS requires an extra oxide layer for the interlayer dielectric between the polysilicon gate material and the first-level metal interconnect. To most beneficially incorporate this oxide into the merged NMOS and thermal inkjet technology, the total oxide underlayer in the merged technology is made up of the thermal field oxide and the chemical vapor deposited (CVD) SiO_2 . This approach allows the use of a thinner thermal oxide layer with a correspondingly shorter growth time, and thus a lower cost.

NMOS technology with two levels of metal interconnect typically uses SiO_2 as the intermetal dielectric and Al as the second-level metal. This is not acceptable for the thermal inkjet structure. The dielectric and conductor layers directly above the thermal inkjet resistor must be thermally, chemically, and mechanically resistant to withstand the elevated temperatures required to boil the ink, the chemical reactivity of the hot ink, and the cavitation-induced mechanical stresses. The $\text{SiN}_x/\text{SiC}_y/\text{Ta}$ passivation layers used in Hewlett-Packard's passive thermal inkjet technology (introduced with the PaintJet and DeskJet printers in 1987 and 1988)^{2,3} offer the required high performance and exceptional reliability. Thus, these films were selected to serve as the intermetal dielectric and the second-level metal in the integrated driver printhead structure.

The final process flow is shown in Fig. 5. Testing has demonstrated that when these materials and processes are used for the merged technologies, they maintain their robustness to the thermal inkjet environment while performing admirably in the role of a double-level metal NMOS IC process.

Manufacturability

Manufacturability is an important consideration in the design and development of a new product that is planned for high-volume production, but it is especially so when very low-cost fabrication is also a major goal. To address this issue, the integrated driver printhead process designers created a solution with the aim of addressing manufacturability at the outset. The circuit design rules were defined to



Fig. 5. Integrated driver printhead process flow.

allow mixing lithographic equipment during the fabrication process. This also allowed the use of mature lithographic equipment. Yield management was also made significantly easier with these design rules.

Furthermore, where feasible, IC operations not required for this product were consolidated or dropped from the process. This created a very simple, low-cost NMOS IC process that could be integrated with the existing thermal inkjet process to meet all of the performance objectives of the product. However, many features of this merged process had not been attempted in a manufacturing environment. Significant efforts to address unexpected manufacturability issues were carried out during the prototyping phase of this project.

Summary

This article has described the successful merging of the well-established NMOS and thermal inkjet technologies in the new HP DeskJet 1200C printhead, resulting in low cost, excellent print quality, and high throughput. Many challenges were encountered in the integration of the two technologies, especially in the areas of multiple uses for the integrated circuit and thermal inkjet thin-film layers. These were successfully overcome through excellent teamwork among the IC process engineering, thermal inkjet process engineering, and printhead design teams from multiple HP divisions and sites. The keys to excellent teamwork and cooperation were communication, clear definition and understanding of goals, and ownership.

Acknowledgments

A project of this magnitude must have many contributors to be successful. The authors wish to thank project manager Eldurkar Bhaskar, Rob Beeson who started the project, Jim Hulings, Jim Grace, Duane Fasen, Rajeev Badyal, Farshad Eteessami, Ellen Tappon, and Leon Wolf who provided design and process definition, and Jerome Beckmann, Stan Gorski, Stan Strathman, Julie Wrazel, Marzio Leban and Skip Rung for their strong management support of the project. Of course, the real success of the project is attributable to the individual and team contributions of the Inkjet Supplies Business Unit and Integrated Circuits Business Division manufacturing teams, the Integrated Circuits Business Division process engineering and design teams in Corvallis and Loveland, and the Inkjet Supplies Business Unit R&D teams in Corvallis and San Diego.

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Development of the HP DeskJet 1200C Print Cartridge Platform

The platform includes all of the parts of the print cartridge except the printhead assembly and the ink. It is designed to accept different printheads and inks to support different printer applications. It features a slim form factor, a spring-bag ink reservoir, and an ink level indicator.

by the Platform Development Team*

The print cartridges for the HP DeskJet 1200C printer and the HP DeskJet 650C large-format drafting plotter (Fig. 1) are derived from a common ink delivery system “platform” to which are added different TAB (tape automated bonding) and printhead assemblies and inks. The platform includes all parts of the print cartridge and packaging except the TAB/printhead assembly and the ink, and brings the following key benefits to printers and customers:

- Flexibility for a wide range of printheads, printing down or sideways
- Slim form factor to reduce the footprint and cost of multi-cartridge printers
- Volumetrically efficient “spring bag” ink delivery with tunable backpressure and ink design independence
- User-friendly ink level indicator usable in and out of the printer
- Ink containment robustness under environmental conditions (thermal, altitude, shipping), combined with environmentally sensitive packaging
- Assembly process improvements such as two times better head alignment and online print quality inspection.

The primary emphasis during development of the platform was design for manufacturability and assembly. This emphasis was key to achieving at least three of the four platform goals. The first goal, to achieve both large capacity and fast time to market, was achieved through simultaneous design, process development, and tooling from the beginning of the project, by early concurrent engineering with vendors, and by the use of “demo tools” for early demonstration of assembly processes and cycle times. The second goal, low cost, was achieved by reducing complexity in parts, processes, controls, and non-value-added steps, by leveraging proven HP assembly processes and designs, and by focusing on manufacturing cost drivers such as tolerances and direct material cost. The third goal, to ensure manufacturability for automated assembly, was achieved by means of “seam teams” made up of R&D and manufacturing engineers and charged with maximizing design for manufacturability and assembly, by organizing the manufacturing line module teams at the start of the project, and by including vendor engineers on the platform design team early in the project. The fourth goal, to meet the needs of multiple cartridges and

* See “Acknowledgments,” page 54.

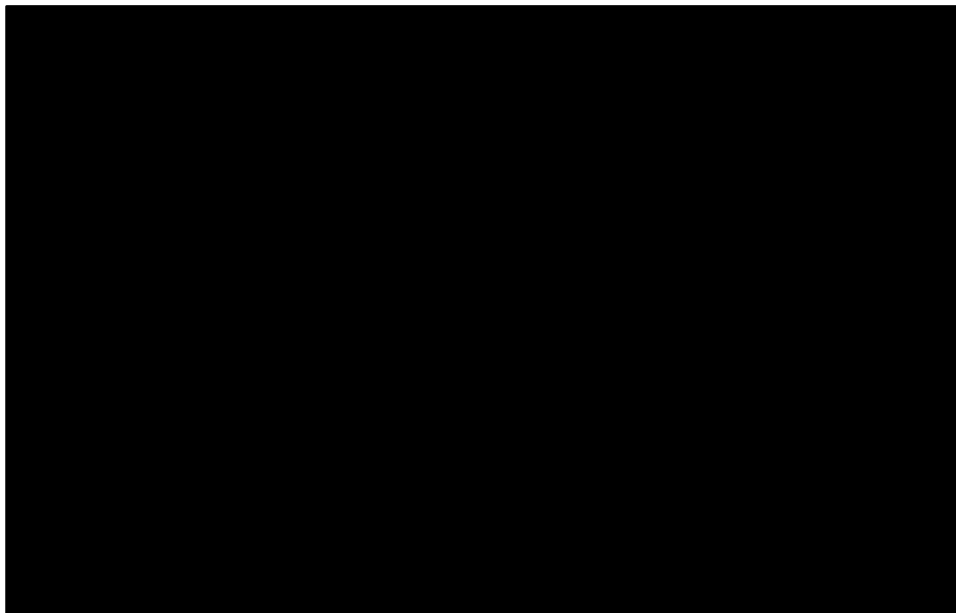


Fig. 1. Print cartridges for the HP DeskJet 1200C printer and DesignJet 650C plotter.

products, was achieved through a design convergence team for multiple printers sharing the platform, and seam teams for cartridge and printer issues.

Seamless and Concurrent Engineering

The design for manufacturability and assembly emphasis was implemented in several ways. The platform engineering team was formed nearly fully staffed, with strong manufacturing influence from the start. The overall team included both R&D and manufacturing engineers and managers. Engineering responsibilities were seamless, with no distinction between R&D and manufacturing engineers. Individual engineers owned broad part design, assembly process development, and tooling responsibilities throughout the project. In this way, design for manufacturability and assembly comes naturally since each engineer designing a part is also developing the assembly processes for that part, and will be responsible for the manufacturing machines to assemble that part.

A second way that the design for manufacturability and assembly emphasis was implemented was through the active concurrent engineering involvement of experienced manufacturing equipment vendors. The vendors' highly experienced engineers were an integral part of the platform design team early. Each month, the vendors' engineers participated in intensive working design review meetings. Between meetings, HP and vendor participants designed and investigated alternatives in preparation for the next joint working session.

Convergence of Platform Design Concepts

The key purpose of designing a platform print cartridge was to enable one common design to satisfy multiple customers in both the office printer and large-format markets. The requirements were to design a low-cost platform in terms of parts and assembly, yet allow for various TAB/printhead assemblies and inks for different products. A narrow form factor in the scanning direction was essential to allow multi-cartridge products a compact desktop footprint. Compatibility with the range of ink types needed for different product applications was also required, preferably decoupled from ink interactions altogether. To accommodate the different ink and architecture needs of different products and applications, the platform's ink delivery starting backpressure needed to be adjustable, both in engineering and on the manufacturing line. Moreover, the overall platform had to be robust and reliable for all products and all customers.

Immediately at the start of platform development a process was needed to set the fundamental design direction quickly for fast time to market, to resolve issues and select among competing concepts, and to ensure that the platform would meet the needs of multiple office printers and large-format plotters. The fundamental platform design direction needed to be set concurrently and interactively. The process used was the convergence team. Functioning within weeks after the project's start, the platform convergence team included representatives from each of the print cartridges and each of the printers. The team met weekly until the key design concepts that strongly affected both print cartridge and printer design were resolved. The key design areas addressed by the platform convergence team included:

- Dot-to-dot alignment requirements, modeling, and effects on print cartridge head and body alignment and printer carriage alignment

- Different print-cartridge-to-carriage alignment datum systems, and their effects on cartridges and printers
- Print cartridge operating orientation in different printers and plotters
- Disposable print cartridge ink volume trade-offs for cost per copy, printer size, and carriage acceleration
- Minimum print cartridge width (printer footprint) consistent with other needs
- Print cartridge form factor aspect ratio (depth-to-height ratio) and related form factor of printers and plotters
- Electrical interconnect configuration and compliance concept
- Ink level indicator needs for each printer and resultant design objectives.

Convergence of the platform design concepts allowed definition of a focused set of design goals to meet the overall platform goals of large production capacity, fast time to market, low cost, manufacturability, robust quality and multiple uses:

- Minimum number of parts and processes
- Narrow form factor for office desktop printing
- Precision alignment to meet print quality goals
- Reliable system electrical interconnect solution
- Inert ink reservoir with tunable backpressure
- Maximum delivered ink volume within narrow form
- Robust leak-free ink containment through shipping and drops
- Ink level indicator for users
- Environmentally friendly minimum packaging
- Print quality tested to specifications
- Quality assurance processes designed along with the print cartridge.

Narrow Form Factor

To meet the objective of a small-footprint desktop printer, the print cartridge size needed to be minimized, especially the width. Narrow width had to be traded off against minimum size for the desired ink volume and printhead layout. From the product objectives, two distinct sets of design features were developed. These sets led to the development of a two-material frame that includes a back-end design to accommodate the ink reservoir assembly and a front-end design to accommodate the printhead assembly (see Fig. 2).

The first set of design features focused on the external geometry of the print cartridge. While it was our goal to minimize print cartridge width, this minimum is constrained by the printhead design and its flexible electrical interconnect circuit. In addition to space for the printhead assembly, room is required for carriage locating features and print cartridge service station functions. Finally, manufacturing tolerances and tooling features must be included to ensure ease of assembly. Besides space constraints, the external frame needed to be rigid for stability in the print cartridge carriage, to withstand temperatures of up to 70°C, and for printhead attachment, to be manufacturable to very tight tolerances.

The requirements of the ink delivery system drove the second set of design features, which focused on the internal frame. The spring bag system required a heat-sealable material that was impervious to the ink and robust under environmental conditions, as discussed later. Tight tolerances and structural rigidity were less of an issue.

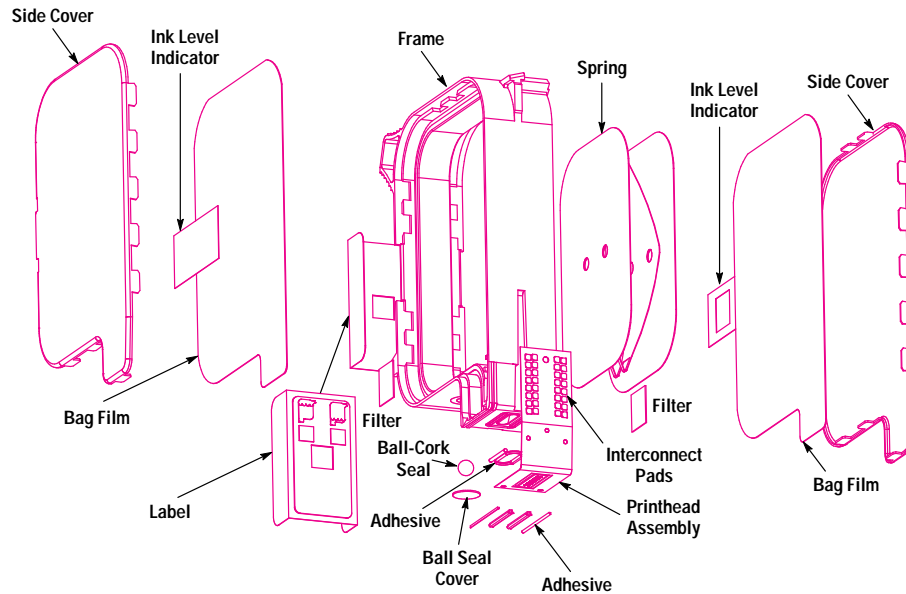


Fig. 2. Exploded view of the HP DeskJet 1200C printer print cartridge.

For both portions of the frame, manufacturability in high volume at low cost were driving objectives. Plastic injection molding is the technology of choice for print cartridge bodies because it meets the objectives of low cost and high volume and is capable of producing complex geometries in engineering materials. The desire to integrate two materials with two sets of design objectives presented an interesting challenge for the plastic injection molding process. Two-shot or “two-color” molding and insert molding have both been demonstrated as feasible.

The final design of the frame was driven not only by the two sets of design features for the external and internal frames, but also by the molding process. General plastic design rules regarding wall thickness and coring of thick sections were combined with the special tooling constraint of the insert and two-color molding processes to arrive at the final design.

The objective of building a thin print cartridge that delivers the most ink for a given overall volume meant that the walls of the reservoir had to be as thin as possible. The two side covers represent the majority of the surface area of the cartridge, which means that the amount of ink that can be contained within the structure is very sensitive to the thickness of the covers. Another key design objective is to keep ink off the customer. If the covers are too thin, a customer might force ink out of the printhead simply by squeezing it too hard during the normal handling expected for a routine cartridge replacement. This consideration led to the concept of “effective thickness,” which is the sum of the actual material thickness plus the deflection of the covers under an applied squeezing load. To prevent ink from being forced out of the printhead, the design rule stated that the inside surface of the covers could never touch the ink containment bag within the structure. When the covers were thin they could be squeezed more, which meant that more dead space had to be included between the covers and the bag to keep the deflected covers from touching the bag. Adding more thickness to the cover material made the covers stiffer, so the effective thickness was reduced and more ink could be held within the structure. The optimum cover thickness was the point where any additional increase in material thickness caused the effective thickness to increase also.

The amount that the covers deflect is primarily a function of the applied load and the material for a given wall thickness. After consulting reference material on ergonomics and performing some quick reality tests, it was determined that an average user would apply less than 10 pounds of force to the covers during normal handling. Covers of varying thickness were made from different thermoplastics and different metals were tested for deflection under the simulated maximum squeezing load. The side cover material that provided the lowest effective thickness and consequently the highest deliverable ink volume from the cartridge was determined to be steel. Prepainted, low-carbon steel was chosen because it meets the environmental requirements and is a standard material in the metal stamping industry.

Attaching the covers to the plastic cartridge frame in a manner that is consistent with high-volume, robust manufacturing objectives was always a concern during the cover development cycle. Adhesives and direct thermal or ultrasonic processes were considered depending on the particular side cover material being investigated. Making the cover from thin steel presented the opportunity to use a tab-in-slot system that requires only a simple mechanical press to attach the covers to the frame. The slot features in the plastic frame are designed to be molded easily and to help pull the frame toward the cover for a tight fit. The mating tabs spaced along the perimeter of the cover are wider than the mating slots so that plastic is displaced when the metal cover is pressed into the plastic frame. The resulting seam makes the system very rigid and is especially effective in resisting loads that tend to twist the cartridge. Tests have shown that the print cartridge structure is very stable at the extreme operating temperatures expected in the printer.

Printhead Assembly and Protection

Electrical contact between the printer and the thermal ink-jet printhead is provided by a flexible conductive component called a TAB circuit, consisting of gold-plated copper traces on a plastic substrate. TAB is an acronym for tape automated bonding, the process used to attach the flexible circuit to the printhead, thus forming the TAB/printhead assembly. Low part cost was a major consideration in the

TAB circuit design. To achieve this, the circuit width was determined solely by the requirements of the trace layout instead of using a standard TAB width. The total circuit area, which is the most important factor in cost, was reduced by roughly 50% as a result.

The TAB circuit design also includes a system to protect the printhead from ESD (electrostatic discharge) damage during handling. The trace layout includes a ground ring surrounding the entire circuit with spark gaps going to each interconnect pad, providing a preferential path for ESD that does not go through the printhead.

The dimensions and locations of the TAB/printhead assembly interconnect pads were designed by a worst-case analysis of both print cartridge and printer part dimensions and the variances in the processes used to put them together. A Monte Carlo analysis was used because of the nonGaussian nature of certain processes and dimensions and because of distribution truncation resulting from inspection processes. Statistical models were created for each part and process based on the most conservative values of part inspection data, assembly process data, part tolerances, and assembly process specifications.

The optimization had to make trade-offs between print cartridge production yields, interconnect reliability, and proper print cartridge fit in the printer. A mechanical seam team composed of engineers and managers from both the print cartridge and the printer was used to balance the risks of all of the proposed changes suggested by the statistical analysis results. To help make these decisions, "What if?" scenarios were simulated for key tolerance variations.

TAB alignment inspection guarantees proper electrical contacts between the product interconnect and print cartridge interconnect pads. The solution is a vision system using a machine recognition algorithm known as blob analysis to measure TAB position. The vision system binarizes the camera field of view based upon a set luminance threshold level. Once the reference target on the TAB is binarized as a blob, TAB position can be calculated with a precision on the order of micrometers.

The TAB circuit is bonded to the print cartridge frame on all four sides of the printhead by heatstaking. This process requires an intermediate film that adheres to both the print cartridge frame and the TAB circuit. The solution is an intermediate thermoplastic film that is laminated to the TAB circuit and heatstaked to the print cartridge frame. Alternatives such as adhesives and ultrasonic welding were ruled out as unwieldy or unreliable. By melting the thermoplastic during the heatstake operation, a mechanical bond is created between the print cartridge frame and the thermoplastic. The mechanical bond is a result of the thermoplastic flowing into the print cartridge frame's microscopic imperfections before solidifying. The heatstake operation involves a balance between time, temperature, and pressure such that the thermoplastic's integrity is not compromised on the one hand nor does poor bonding result on the other. The parameters were optimized by the design-of-experiments method to achieve the best peel force resistance.

Two adhesives are used in the print cartridge assembly. The first is a thermally cured epoxy that is dispensed on the plastic frame around the ink feed slot. The epoxy is used to

attach the printhead to the frame and to provide a seal to keep the ink from leaking out of the ink reservoir and air from leaking in. The second adhesive is used to encapsulate the exposed TAB conductors that extend from the flexible circuit to the printhead. These beams are bonded to pads on the printhead to provide electrical connection from the TAB circuit. The dispensed adhesive flows around the conductors and provides a robust protective coating for the fragile TAB beams after it has been cured. The second adhesive is also dispensed along the edges of the TAB circuit to help adhere it to the cartridge frame.

Ink Containment and Pressure Control

The function of the ink delivery system is to contain the ink and deliver it to a thermal inkjet printhead at a predetermined pressure for the life of the print cartridge. The ink delivery system's major design objective was to be a platform to accommodate assorted printheads and thus permit the development of different print cartridges while keeping costs down. In previous-generation disposable print cartridges various methods of ink containment and pressure control were used, the main ones being the collapsible rubber diaphragm for the HP ThinkJet printer cartridges, in which ink is retained via the elastic nature of the bladder, and the porous foam material for HP DeskJet and PaintJet printer cartridges, in which capillary forces retain the ink. These print cartridges are adequate for their specific printer applications but did not qualify as the next-generation ink delivery system platform because of their larger size (especially in the printer scan axis), higher cost per page, ink compatibility limitations, and indirect backpressure control. Therefore, the print cartridge design group had to develop a completely different concept that would overcome the weaknesses and constraints of previous-generation cartridges while allowing the possibility of adding new features such as the ink level indicator. This new ink delivery system and platform is called the spring-bag design and is based on the principle that ink is contained in a flexible envelope formed of films and a mechanical spring is biased against these films, thus creating subatmospheric pressure within the system.

Spring-Bag Print Cartridge

Conceptually, the print cartridge is in a "tug of war" situation between the negative pressure generated by the spring of the ink delivery system and the capillary forces generated by the tiny nozzles of the printhead. The firing chamber acts as a micropump each time it ejects a droplet of ink and refills itself by capillary action. As droplets of ink are fired, the ink in the spring bag gets depleted and this process goes on during the life of the print cartridge to a point where the firing chambers cannot be refilled. The print cartridge is then replaced with a full one.

The major components of the spring-bag print cartridge are a molded plastic frame, two flexible plastic films, a spring assembly, two filters, two covers, and a ball-cork and patch (see Fig. 2).

The frame is molded using two different plastics. The outer shell is made of a stiff plastic because it is the skeleton of the design to which other parts will be attached, and the inner shell is made of a rubber-like plastic to permit a fluidic coupling to the outer shell and to allow for heatstake processes. The fluidic coupling is needed to provide a leak-free joint

Print Cartridges for a Large-Format Color Inkjet Drafting Plotter

While the DeskJet 1200C cartridge development team focused on applying HP inkjet technology to develop a desktop plain paper color solution, the DesignJet 650 cartridge design team used the same technology to introduce color into HP large-format inkjet plotters. The original HP DesignJet plotter¹ and the high-resolution DesignJet 600 plotter brought the print quality, reliability, and user friendliness of inkjet technology to the large-format plotter market. The full-color DeskJet 650C plotter opens up new applications that were not possible with single-color plotters.

The DesignJet and DesignJet 600 use two HP DeskJet print cartridges, which have proven reliable through many years of experience with the DeskJet family of products. When the DesignJet team set out to develop the first large-format color thermal inkjet plotter, the DesignJet 650C, the challenge for the print cartridge design team was to develop a four-print-cartridge system that would continue to meet or exceed customer expectations for print quality and reliability. The best way to deliver color inkjet technology into this marketplace was through a highly leveraged program that could meet the objectives with a quick time to market and minimal staffing levels.

DesignJet 650C Black Print Cartridge

One of the main requirements for the black print cartridge for the DesignJet 650C plotter was to deliver uncompromising print quality and reliability at a relatively low cost. To minimize the expense and time invested in engineering, development, and marketing, the decision was made not to develop a new black print cartridge but to use the black cartridge developed for the DeskJet 1200C printer. This allowed us to take advantage of the media independence, water fastness, and light fastness of the new black ink, but it posed a challenge because this black print cartridge is optimized for a small-format writing system that employs a heater and a fan to minimize the print quality effects of the vehicle used in the black ink formulation. The objective for the DesignJet 650C plotter was to deliver optimal print quality on a variety of media including HP CX Series JetPaper (PaintJet paper), all of the plotter media (bonds, vellums, translucent), and a specially developed thermal inkjet film. The engineering development team focused on meeting customer expectations for large-format print quality without any sacrifice of environmental range or performance compared to previous products.

The drop volume of the DeskJet 1200C black print cartridge was chosen so that the ink put down in a full area fill will just cover the media surface (this is known as closure). Any additional ink would contribute to unnecessary cockling of the

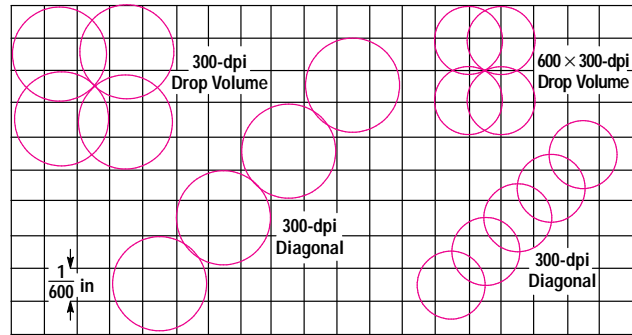


Fig. 1. In its monochrome enhanced mode the DesignJet 650C plotter plots vector data at 600-by-600-dpi resolution and filled areas at 600-by-300-dpi.

paper, color-to-color bleed, and excessive drying time. The drop volume was selected according to the DeskJet 1200C's goal of placing two black dots per 300-dpi pixel on plain paper. However, the DeskJet 1200C uses a heater to promote drying, and office-use media are typically more absorbent than large-format plotter media. Thus, the appropriate drop volume for the DesignJet 650C plotter is more nearly 1.75 drops per pixel. To achieve this noninteger density, the DesignJet 650C plotter implements a dot-depletion algorithm. It first rasterizes any vector data at 300 dpi and merges it with any 300-dpi raw raster data. It then doubles each pixel in the carriage direction (the scan axis), producing a 600-by-300-dpi bitmap. The plotter then examines the bitmap for regions with fill densities greater than 1.75 dots per pixel (the maximum will be 2 dots per pixel). When it finds such regions it turns off some of the pixels in the interior to reduce the print density, while preserving the pixels that define the edge of the fill. The algorithm is implemented as a user-selectable "contrast level" so that users can select maximum fill densities of 1.5, 1.75, or 2.0 drops per pixel according to the ambient conditions.

The DesignJet 650C plotter further exploits the small drop volume of the DeskJet 1200C black print cartridge in its plain paper monochrome enhanced mode (Fig. 1). As mentioned above, the diameter of the dots is approximately sized for 600-by-300-dpi printing. In enhanced mode, the vector data is rasterized at a full 600-by-600-dpi resolution. The printer can place a drop on any 600-dpi pixel by

between the outer shell to which the TAB/printhead assembly is attached and the inner shell to which the ink delivery system is attached. The two filters, used to stop particulate contamination from reaching the small fluid passages in the printhead, are also heatstaked to the inner shell.

The spring assembly consists of two flat metal plates attached to a pair of metal leaf springs. The flat plates are covered with a thick plastic shield to prevent the edges from cutting the films and to allow stabilization of the assembly relative to the films. The principle behind the spring design is to transfer the force generated by the spring to the metal plates which in turn push out on the films. This generates the backpressure in the system, which must be controlled very closely because it directly affects the print quality. If the system is at a backpressure less than one inch of water, there is a high risk that ink will drool out of the nozzles, and if the backpressure is greater than eleven or twelve inches of water, the time to refill the firing chamber increases and the volume of the ejected drop decreases, decreasing the print quality. Using Bernoulli's equation, these initial and final pressure values were used to determine the spring's force range. The challenge was to design a spring with a low

spring rate and yet a relatively high starting force. This required a spring that would exhibit a constant stress throughout the beam for a given deflection. This was achieved by giving the leaf spring a diamond geometry so that the force generated by the spring as a function of the curvature of the spring remains constant during the life of the print cartridge (Fig. 3).

The films are heatstaked on each side of the inner shell of the frame. The film itself is a multilayer aggregate that strikes a delicate balance between flexibility and water vapor loss. Flexibility is needed to get the most ink out of the reservoir, while metallizing the film to reduce the amount of water loss and permit a low-cost, nonhermetic package design tends to diminish the delivered volume. The spring is introduced during assembly between the two films and begins exerting an outward force on them.

The two covers, which are made of metal for stiffness, are pressed into the outer shell and make the structure very stiff. Ink is then filled into the ink delivery system followed by the insertion of the ball-cork into the frame. Following this, the system is primed by removing all of the air through the nozzles and initiating their capillary forces.

half-stepping the media drive. It scans over the media, firing 96 nozzles on a grid that has 300 dpi vertically but 600 dpi horizontally. It then advances the media by 1/600 inch and scans again, filling in the swath to full 600-by-600-dpi resolution. (The printer actually advances the media alternately by 48.5/300 inch and 47.5/300 inch, moving back and forth between the two 600-by-300-dpi grids while also interlacing the printing passes by half a swath. This masks some mechanical errors in media advance and print cartridge alignment and mitigates some ink-media problems.) However, true 600-by-600-dpi density uses too much ink with a drop volume designed for 600-by-300-dpi printing. Therefore, before printing the data, the plotter depletes the interior of filled regions to an average of 600-by-300-dpi density, while preserving pixels that contribute to 600-dpi edge acuity. This leaves approximately 2 dots per 300-dpi square, or 0.5 dot per 600-dpi pixel. The data is then further depleted to a user-selected contrast level to promote faster drying. The result is a plot that is nearly indistinguishable from true 600-dpi output, using a minimal amount of ink from a print cartridge that delivers twice the drop volume of a 600-dpi cartridge.

DesignJet 650C Color Print Cartridges

Current plain paper color inkjet technology uses a heater and fan system to drive off excess water and dry the ink, as in the HP DeskJet 1200C printer. It was neither cost-effective nor technically feasible to put a heater and fan system on a large-format plotter, making a special paper color solution the best alternative. Since the DeskJet 1200C color print cartridges were being optimized for a plain paper color solution, they could not be expected to perform well in a DesignJet 650C.

The color inks and special paper used in the HP PaintJet printer² were directly leveraged into the DesignJet 650C plotter. Using preexisting ink and media provided some stability to the program but also removed the flexibility to optimize them for our new application. Any performance problems that arose would have to be solved elsewhere. Having this stability we could concentrate on developing the printhead architecture and ink delivery system.

The development of the ink delivery system is where the most leverage was obtained. As described in the accompanying article, the platform print cartridge is designed for successful leveraging. Most parts and processes are shared between the DeskJet 1200C and DesignJet 650C color print cartridge families. Only where absolutely necessary are there differences in parts or processes (i.e., TAB/printhead assemblies, inks, packaging).

The only area where there was a large amount of design freedom available was in the design of the printhead architecture. The flexibility in this area allowed us to

meet the particular demands of the large-format market. The ability to create the thin, well-defined lines required in CAD applications is crucial for any technology trying to compete in this market. The ramifications of this requirement dictated a drop volume design center below any other HP thermal inkjet print cartridge to date. To meet the 0.13-mm linewidth specification required that the drop volume design center be set at 30 pl. For comparison, the original DeskJet print cartridges are designed to deliver 130 pl. The need to deliver such a small drop volume pushed the architecture to new limits by requiring very stable drop ejection to maintain uniform area fill quality. Advances in thin-film processing coupled with a new architecture design allowed us to meet these objectives. This proved to be an important effort, since the knowledge gained is directly applicable to higher-resolution inkjet designs.

Concern over excessive printhead temperature was another design area that needed attention because of the large-format nature of the application. Since this print cartridge would be printing 34-inch swaths for a duration of several minutes, the performance of the print cartridge had to be ensured at elevated temperatures. The approach that was chosen was to minimize the amount of heat buildup in the head by optimizing the architecture to deliver the ink in a thermally efficient manner.

Conclusion

The DesignJet 650C print cartridges have proven to be successful in meeting and exceeding customer expectations. Their level of performance was verified through extensive testing of the print cartridge and product system. This testing has demonstrated a significant improvement in writing system reliability compared to pen plotters. Pen plotters require frequent pen changes to keep plotting. The DesignJet 650C print cartridges have been designed to require less frequent customer interaction, making them more user-friendly. This provides customers the benefit of unattended use such as overnight plotting.

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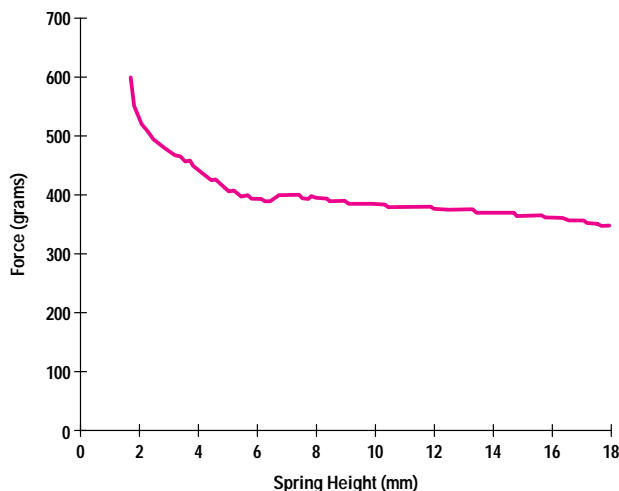


Fig. 3. The force exerted on the ink bag by the print cartridge spring is relatively independent of spring curvature.

Major Benefits of the Spring-Bag Ink Print Cartridge

The spring-bag design allowed us to meet and exceed many expectations we had set as goals. The design permits the use of known, controllable materials for the spring, frame, and film, and is compatible with many inks, thus making this design a platform. Using a spring-bag design results in a mechanically controlled system. The spring makes a tunable system possible, allowing selectable starting backpressure. The closed system is air-free and does not allow any air to get in. This makes the print cartridge very tolerant of environmental conditions such as thermal and altitude changes. The closed nature of the system and the multilayer film result in very low water loss through the membrane, making it possible to do away with the aluminum can shipping container in favor of a simple paper box which is environmentally sensitive (see "Environmentally Friendly Packaging" on page 53).

Environmental and Shipping Robustness

A key objective for the print cartridge is that the ink stays in the print cartridge and doesn't get on the customer. To ensure this robustness in both design and assembly, frequent

build/test/fix cycles were used. When tests were failed, causes were determined and a fix implemented even if that meant adding parts or engineering a custom material.

Early in the project, a test cycle to demonstrate robustness was defined and a design defect tracking system was put in place to keep track of all print cartridge problems (not just robustness-related ones). The tests fall into two major categories: survival and shipping simulation. Survival tests are done with the cartridge untaped and unpackaged and are designed to mimic customer abuse. These are severe tests and the requirement for passing is that no ink leakage or hazard (sharp edges, etc.) be observed. Shipping simulation tests are done with the cartridge taped and packaged and are designed to mimic the stresses the print cartridge will see in transportation and warehouse storage. The requirements for passing are that no ink leakage occur and that the print cartridge be printable, that is, capable of printing. The tests include free drops (multiple drops from one meter onto concrete in different orientations), vibration (both random and swept), temperature cycling (-40°C to $+70^{\circ}\text{C}$), hot soak (65°C , 90% relative humidity for one day), and altitude.

The last related test is water loss, measured as water vapor transmission rate or WVTR. This is important because the ink will work correctly only over a narrow band of water content. There is no official standard, so one was developed. Our in-package shelf-life requirement is 18 months at 25°C . Our in-product goal is 6 months in heated printers (potentially with the heater in the standby “warm” mode around the clock) at well above ambient temperature.

The print cartridge performed well at high altitude or temperature in part because the vent-free, collapsible, flexible design minimizes trapped air volume and provides compliance against air expansion forces. Numerous small problems were uncovered and fixed, too many to cover here. Briefly, they included ink level shift (showing partially out of ink when full) after drop, spring hangups on the frame (stranding excess ink), air intrusion through the ball-cork seal after temperature cycling (causing loss of backpressure), and side covers popping out of the frame after drop (causing print cartridge alignment errors).

The four biggest problems were WVTR, ink leakage from the bag-film-to-frame seal, ink leakage from spring-induced tears in the bag film, and ink wicking under the nozzle tape. The WVTR problem was made easier to solve by the vent-free design (vents are usually a large loss path), and by the low-water-loss second-shot plastic. But it was complicated by the large bag film area and the need for the film to be extremely flexible for reasonable backpressure and delivered volume performance. Most applications require low water loss or flexibility, not both. This required a custom film structure. Standard materials and assembly processes were used. After numerous iterations the nine-layer film structure shown in Fig. 4 was selected.

The second major problem was the bag film peeling away from the frame at the seal joint during drop testing, causing major ink leakage. During a drop, a lot of ink is pushing down on the film near the seal just as the frame is pulling the frame up at the seal edge, producing a severe reverse peel (the worst kind of load) on the seal. The original second-shot plastic material was HDPE, which is not a very good



Fig. 4. Nine-layer bag film structure.

sealant. A burst test was developed to characterize seal strength (internally pressurize a sealed spring bag until the seal ruptures or the bag film breaks like a balloon). Optimization of the seal parameters (time, temperature, and pressure) and adjustment of the mechanical tooling tripled the burst pressure. At this point a single two-meter drop or four one-meter drops could be survived. This indicated that a single drop caused partial seal peel. While very few print cartridges were likely to see four drops, we hadn’t tested millions of print cartridges, so the ultimate margin was not known. A material search was instituted and a new second-shot material was selected that has much higher seal strength. Burst strength tripled and the bag film breaks before the seal peels.

The third major problem was the metal spring piercing the bag film in drop or vibration testing, causing moderate ink leakage. The piston plate part of the spring is very thin and has a rough, burred edge that is right up against the bag film. Attaching the spring to the film eliminated the drop failures but aggravated the vibration failures (fixed the relative motion to one spot). The solution is a plastic shield over the spring piston plate (the shield is larger than the plate). Thus, no matter how rough the plate edge or how the bag film wraps the plate edge, direct metal contact is not possible.

Plastic tape is used to seal the nozzles during shipping and storage, thus preventing failure of the device as a result of orifices becoming clogged by contamination or dried and crusted ink. The tape must seal securely on the nozzle plate but must also be easily removed before use without damaging the print cartridge or leaving any adhesive residue on the nozzle plate. Tape manufacturing and alignment considerations result in the tape being considerably wider than the nozzle plate so that it extends over the encapsulant beads (see Figs. 5a and 5b). This resulted in a peeling load on the tape in the nozzle region. During high-temperature storage the tape peeled off over the nozzles, leading to wicked ink and some crusted ink nozzle plugs (Fig. 5c). The solution is two slits in the tape just before assembly to decouple the regions of tape over the nozzles and over the encapsulant beads (Fig. 5d). The free end of the tape is then wrapped over a printed paper customer pull tab to provide an easy method of removal.

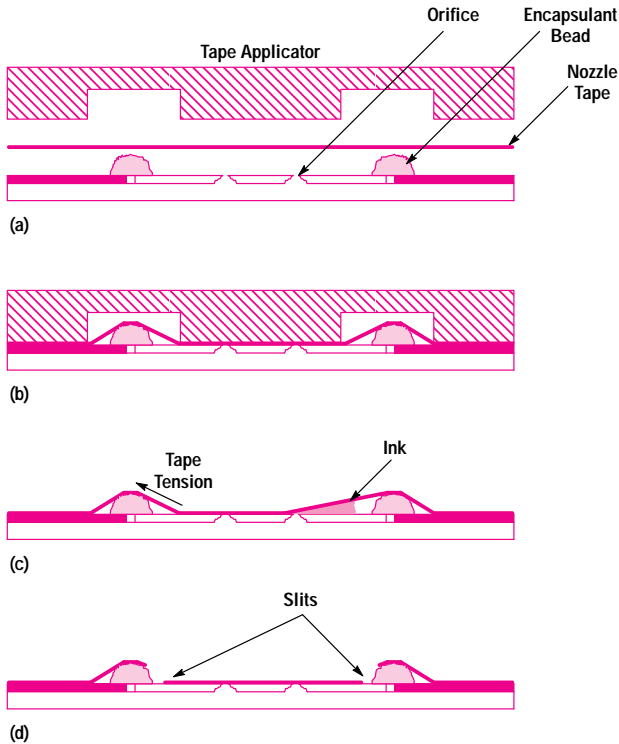


Fig. 5. (a) Tape is placed over the orifice plate of the printhead to prevent leakage during shipping and storage. (b) The applicator deflects the tape down between the encapsulant beads. (c) Residual tension in the tape at the beads tended to peel the tape up from the orifices. (d) Slits in the tape decouple the tape over the beads from the tape over the orifices.

Ink Level Indicator

During the initial design phase of the DeskJet 1200C print cartridge it was decided that the cartridge should have an ink level indicator. The primary intent of this indicator is to warn the customer so as to prevent losing a printed page because of a print cartridge that is out of ink. The DeskJet 1200C print cartridge will be the first HP inkjet print cartridge with an ink level indicator. Consumer demand for level information is increasing, fueled by indicators in copiers and laser printers showing toner cartridge life and by the larger volumes of printing customers are doing. Knowing a print cartridge is low on ink is helpful before printing a large number of graphics pages. It gives the user time to purchase a replacement print cartridge, provides an indication of which of the color print cartridges is empty, and identifies whether a print cartridge that does not print properly is out of ink or has another problem such as a deprime.

More than 20 methods of implementing an ink level indicator were considered but most either did not meet the required objectives or were too expensive. Building the print cartridge with clear covers and clear films would be very difficult to achieve, and even if achievable would not give the customer a clear ink level indication since the ink level does not drop in a spring-bag print cartridge. Measuring the bulk conductivity of the ink and counting the drops a print cartridge has fired were two of the leading alternatives. The current design has many advantages over these, a primary advantage being that the ink level indicator is independent of the printer.

Environmentally Friendly Packaging

The package design for HP DeskJet 1200C print cartridges represents an advance in thermal inkjet packaging with respect to both environmental friendliness and unit cost. Responding to customer needs and requests for less waste (and hence less landfill), it was an early design objective of the ink delivery system that the print cartridge itself should provide sufficient water vapor transmission barrier and shipping robustness without requiring additional layers of protection from the package. Meeting these objectives and designing the package concurrently with the cartridge results in a new package that has many advantages both for the customer and for HP.

The print cartridge package has only two parts: a paper insert for customer communications and a recyclable paperboard carton. The carton is a one-piece design with air cells protecting the cartridge on four of the six sides. The manufacturing process involves erecting the carton, inserting the cartridge and paper insert into the carton, and sealing the two ends of the carton with hot melt glue.

Fig. 1 shows exploded views of the existing package design and the DeskJet 1200C package. The DeskJet 1200C design reduces the number of parts from six to two, eliminates the expensive aluminum parts, reduces the number of materials from four to two, reduces the number of process steps and machines from two to one, and reduces the ratio of package to print cartridge volume and weight.

The DeskJet 1200C print cartridge package has received the approval of the Green Dot program in Germany for its sensitivity to environmental and recycling issues.

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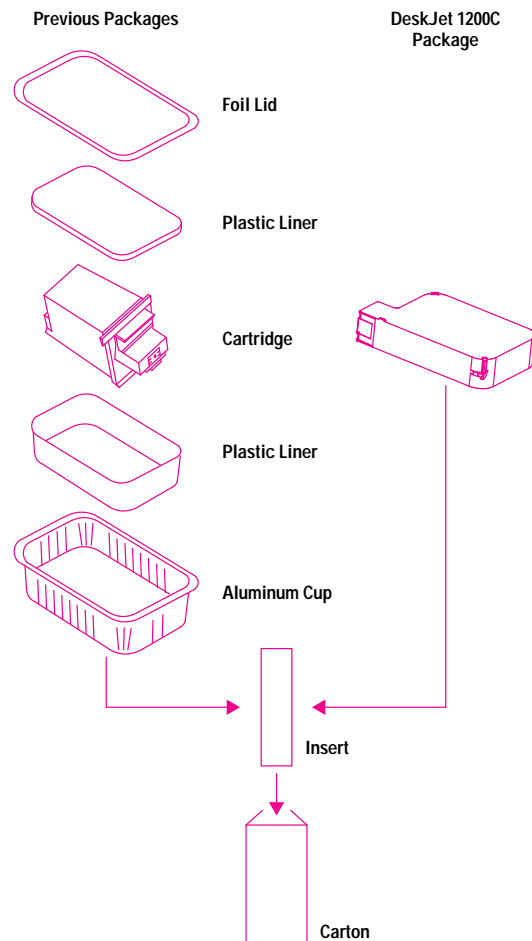


Fig. 1. Comparison of existing and DeskJet 1200C print cartridge packages.



Fig. 6. Ink level indicator. (left) Full. (center) Partially empty. (right) Empty.

The design selected is called the dual-flag design (Fig. 6). It consists of two strips (flags) of film attached to either side of the spring bag. One flag is solid green and the other is black and has a rectangular hole cut in it. The flags overlap across the front of the print cartridge with the black flag over the green so that the green can be viewed through the hole in the black flag. An adhesive label covers both flags and provides a window to the indicator. As the ink volume decreases, the two sides of the bag collapse towards each other, moving the flags with them. The amount of overlap indicates the approximate amount of ink remaining in the print cartridge (Fig. 7). The amount of ink is indicated regardless of whether the two sides of the spring bag collapse together or not. When the print cartridge reaches low ink, no green is visible in the viewing window, only black. One half of the black rectangle in the viewing window is the black flag. The other half is actually the print cartridge body showing through the hole in the black flag.

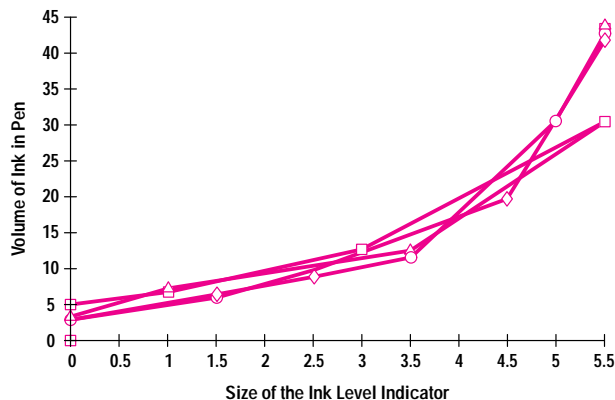


Fig. 7. Size of the green ink level indicator as a function of ink level.

The design objective for the ink level indicator was to show full (all green) when a print cartridge ships and low (all black) when the ink level is within $\pm 10\%$ of the low ink point. This is a reasonable goal that delivers information similar to an automobile fuel gauge. Any greater accuracy would be both unnecessary and difficult to manufacture.

Acknowledgments

The writing of this article, like the development of the print cartridge platform, was a team effort involving many contributors. They include the three project managers and the seamless R&D manufacturing engineering staff, each of whom had broad responsibilities in R&D, process development, and manufacturing tooling and are listed below.

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- Steve Bauer, TAB circuit wrap and side stake
- Dustin Blair, filter and cover assembly and tooling
- Hendrick Brower, THA adhesive and encapsulant
- Erich Coiner, spring forming and system leak testing
- Mindy Hamlin, frame design/molding and THA attach
- Dave Hunt, ink level sensor design and assembly
- Rob Little, TAB cheek stake and surface treatment process
- Tony Panah, spring design and assembly
- Bruce Reid, TAB design and orifice taping
- Joe Scheffelin, ink bag materials and assembly
- Jeff Thoman, precision alignment machining and measurement
- Dale Timm, cover and adhesive development/cure
- Amy Van Liew, environmental and shipping robustness.

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HP DeskJet 1200C Printer Architecture

The product architecture of the HP DeskJet 1200C printer—mechanical, electrical, and firmware—played a key role in addressing the technical challenges demanded by the office color printer market.

by Kevin M. Bockman, Anton Tabar, Erol Erturk, Robert R. Giles, and William H. Schwiebert

In office printers, not only are speed and low cost paramount, but also print quality and the emerging use of color. The HP DeskJet 1200C printer was conceived to address these issues. This article discusses the printer's architecture and its development.

The primary applications for this printer are laser-quality black text, spot color, full color, and transparencies. Challenges for the design team were achieving print quality and speed goals for these applications, becoming LaserJet compatible, achieving small size and ease of use for the office, and designing for high-volume production.

The major performance features of the HP DeskJet 1200C Printer include:

- LaserJet-equivalent print quality
- 300-dpi color
- Outstanding color quality
- Six-page-per-minute text speed
- Four-page-per-minute high-quality mode
- One-to-two-minute-per-page color speed
- Industry leading color cost per copy.

The major usability features of the HP DeskJet 1200C printer include:

- Full range of media supported, including plain paper (copier to bond), special paper, overhead film, glossy paper
- Dual media path, with label stock and envelopes manually feed through the rear path
- LaserJet IV compatibility
- PCL 5C color language
- Four-print-cartridge operation
- Upgradability to PostScript™ Level 2 language (standard in the DeskJet 1200C/PS)
- Expandability using HP MIO (modular IO) boards
- LaserJet font cartridge slot
- 45 internal scalable fonts.

The DeskJet 1200C carriage holds four print cartridges: black and three primary colors (cyan, magenta, and yellow). Printing is accomplished by traversing the cartridges back and forth and using a linear encoder to fire drops of ink onto the page. Black text is printed with the black print cartridge and color is created using a combination of dots fired from the color print cartridges (e.g., red consists of magenta and yellow). All of the colors of the rainbow can be created using a dithering process. The cartridge carriage also holds an optical sensor which is used for paper size sensing and to differentiate between transparency film and other media.

A print cartridge service station caps the inkjet cartridges to prevent the ink from drying out when the printer is not in use. The service station includes four separate wipers to help maintain a clean nozzle plate for optimum print quality. Also included is a manually selectable and manually activated reprinter that is used to clear nonfunctioning nozzles.

The dual media path is designed to support a range of media types and sizes. Typical A-size, metric A4, and legal-size media can be fed automatically through an input tray in the front. Common LaserJet labels, overhead transparencies, and glossy media can also be fed automatically. Single sheets, card stock, and a range of envelopes can be fed manually through the rear path.

The printer can connect to a wide range of systems. A Centronics interface is standard and an HP MIO slot allows connection to a range of other interfaces including networks. The base unit is expandable from the standard 2M bytes of memory up to 26M bytes by inserting industry-standard SIMMs through a slot in the rear. The printer is upgradable to a Postscript Level 2 machine or it can be purchased that way.

Technical Challenges

Print Quality. To compete in the office market, the DeskJet 1200C had to have excellent print quality on all plain paper media. This includes standard copier paper as well as bonds in the 16-to-30-pound range. Capillary action between the ink and the media, which can result in ink wicking along the paper fibers and causing fuzzy characters, is overcome with a solution that includes new inks and a heated paper path. Because jagged off-axis characters are perceived as low-quality, the scan axis resolution was increased to 600 dpi and HP Resolution Enhancement technology is employed, greatly improving the appearance of the characters' edges.

To gain media independence and good media advance accuracy, a heated paper path is provided. The purpose of the heater is to aid the ink drying process without overcooking or browning the media. Where typical printers have used large rubber rollers to advance the media, for the heated path a small, accurate, and heat resistant system needed to be developed. Adhesive-bonded grit particles on small cylindrical drive wheels have long been used on many Hewlett-Packard products as a media drive system. However, the adhesive would not stand up to the temperatures in the heated media path, so a tungsten carbide grit was developed

CAD System Organization

Early in the HP DeskJet 1200C printer project, we came to realize the power and efficiency of designing with a solid modeler CAD system. Our early testbeds and breadboards were designed on this type of system. All of the parts of, say, a breadboard were contained in three-dimensional bodies on the CAD system. Because the parts were all positioned correctly relative to one another, the breadboard was essentially designed and assembled on the CAD system before a single part was ever made!

The solid bodies representing the assorted parts were sent to the model shop without having to create detailed two-dimensional drawings. This was a real time saver. The model shop then used the solid bodies to generate tool paths to machine the various parts or had the solid bodies rapid prototyped by one of our several rapid prototype vendors. The parts that came back all fit perfectly. Even moving mechanisms could be analyzed on the CAD system and debugged before ever making a part. This certainly wasn't like the old days of drafting boards, overlays, and eraser crumbs.

We realized from our early successes that the solid modeler was indeed a powerful tool. Conceptualizing, designing, integrating parts into an assembly on the CAD system, and finally submitting the parts to be prototyped without elaborate 2D documentation has made this a much more efficient process than ever before.

The HP DeskJet 1200C printer project team made the decision to set up an organized part structure on the CAD system to exploit this new capability. The organized part structure contained all the parts for the product we were just defining the architecture on.

The part structure broke the machine into its major subsystems and parts and put them all in a central file area available to all HP DeskJet 1200C printer designers. From this point, our large design team evolved the individual part designs, keeping the most current revisions in the central file, readily available to anyone who might need them.

Thus, this central file on the CAD system contained solid models of all of the parts of the printer. The models were the latest revisions and they were all positioned from a common coordinate system so that they fit together correctly on the CAD system. The design team essentially conceptualized, designed, integrated, and assembled the product on the CAD system.

It turned out to be a valuable communication tool between designers as well. The central file was used continuously throughout the development of the printer as a fundamental design tool.

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to meet all the requirements for accuracy, heat resistance, and traction capability.

Speed. Current users of black and white lasers are accustomed to print speeds of four to eight pages per minute. Current thermal inkjet printers are throughput-limited by several factors including firing frequency, retrace velocity, acceleration, and sheet-feed time. The scanning technology requires the carriage, which weighs over 1.5 pounds, to accelerate and stabilize accurately and quickly before it is ready to print. High-performance servos are required to accelerate, scan, decelerate, and return the carriage to produce each line of text. The paper axis motor's advance time needs to match the scan axis turnaround time in both length and accuracy. Adding a motor to the sheet feeder reduces the waiting required between printing successive sheets. To control these

functions, a fast hardware system and optimized firmware are required.

LaserJet Compatibility. To be compatible with the HP LaserJet print margins, the design team found it necessary to define the interface between the print cartridge and the media path for good control over the media. At both the top and the bottom of the page, the physical sheet experiences a handoff to or from a set of drive wheels. This interface is a source for potential print quality errors especially during full area fills or the splitting of large text in the handoff region.

Size. With desktop space at a premium, the product size was under scrutiny all the time. An overall limitation was set on the size and the design team was challenged to operate within it. At every step of the way each design decision had to address the question, "Can it be made smaller or can it be eliminated?" One benefit of small size is the often overlooked aspect of shipping. Since most of the shipping cost comes from the size rather than the weight, the overall exterior dimensions are critical. In addition, the products are shipped on discrete pallets of a predetermined standard size, which has an influence on packaging efficiency.

High-Volume Production. A sharp focus was placed on low-cost manufacturing and product assemblability right from the start. Detailed attention was given to each system to choose the best technology for both functionality and cost and to scrutinize the way in which the parts were assembled. A lot of attention was given to ergonomic aspects of the assembly process as the cycle times were reduced and the possibility for repetitive motion injuries increased. In most cases, a solution came from changing the design, designing special dedicated assembly tooling, or using a highly automated assembly line.

Product Architecture

The product architecture establishes the boundaries of the product, provides a path to successful development of the product, and defines the product's fundamental feature set. The major systems defined by the DeskJet 1200C product architecture are the electrical system, the firmware system, and the mechanical system.

The architecture defines the layout of the machine by identifying the subsystem boundaries and component locations and by defining how the various designs integrate. It addresses issues such as user interfaces (how will the paper be loaded?), manufacturing processes for individual parts, manufacturing assembly of the whole product, and servicing of the product by company service representatives.

As a process, the product architecture acts as an organizational structure within which the individual designs are developed. It provides a negotiation mechanism between the various groups defining the product features.

Fast-track development of the DeskJet 1200C printer did not affect the product architecture as much as it did parts development, where rapid prototyping was necessary to squeeze time out of the schedule. Still, there was a continual emphasis placed on reducing design risks and consequently the

potential for project delays. This conservative design approach provided substantial time savings throughout the project.

Evolution of the Architecture

The HP DeskJet 1200C printer project inherited a large body of work, both theoretical and physical, from an earlier project, which developed a low-cost color printer for the office using two print cartridges (black and tricolor). Work on that printer determined a basic media path and a set of features that now drove the new project. Both the old and the new printers are A-size, small-footprint office printers with 300-dpi resolution for both black and color.

Increasing the number of print cartridges in the new product from two to four was perhaps the most dramatic change from the earlier project. The mainstream office was still the target market but the new project team also had to recognize that office users were now expecting more from a color printer, such as lower cost, smaller footprint, better color, faster printing throughput, and easier connectivity. This changing set of expectations established a moving target that required the project team to accept a very ambitious feature set for the new printer.

Early in the investigation phase of the project, perhaps because of the head start provided by the earlier project, a prototype of the new printer was built that represented most of the functionality of the final product. This prototype gave the project a physical reality and greater stability in the eyes and minds of the project team. At this point, the prototype had incomplete electronics and no case parts. It implemented a simple I/O system and had no expandable memory. Two sheet-feed paths were included (one automatic and a second customer-installable rear path) and throughput was rated at about four pages per minute. Fig. 1a shows this early prototype. It provided many important lessons, pointed out some vendor problems, and resulted in several feature changes.

Concurrent with the HP DeskJet 1200C printer project, development of the HP PaintJet XL300 printer, a B-size, 300-dpi color inkjet printer, was providing a body of good, practical experience that the DeskJet 1200C printer team could learn from. From this experience, the DeskJet 1200C team realized the importance of defining the printer early in the product development cycle and of minimizing "creeping featurism." The PaintJet XL300 printer experience also highlighted the need for several feature improvements, including better paper control to reduce curl and cockle, spray reduction by placing the vacuum closer to the print cartridges, shims to stabilize the paper, more closely spaced drive rollers to control the paper and improve accuracy, improved chassis stability, and greater shock resistance.

Market surveys now showed that the office user had higher expectations for a color printer than previously imagined. In defining a new, expanded feature set, the DeskJet 1200C project team realized that the office market would support provisions for stronger connectivity with a modular I/O system (HP MIO), expandable memory using customer-installable SIMMs, a PostScript Level 2 option, also customer-installable, and greatly improved throughput matching that of a midrange laser printer.

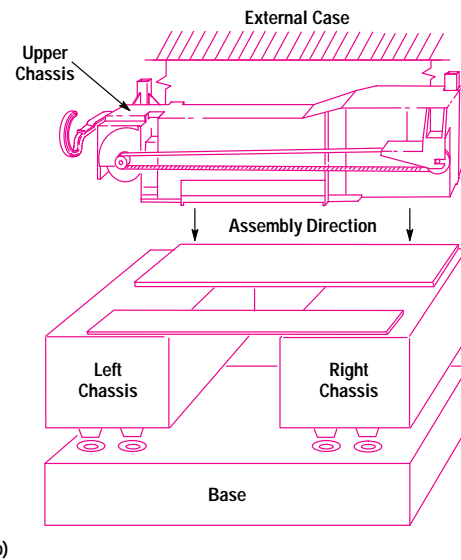
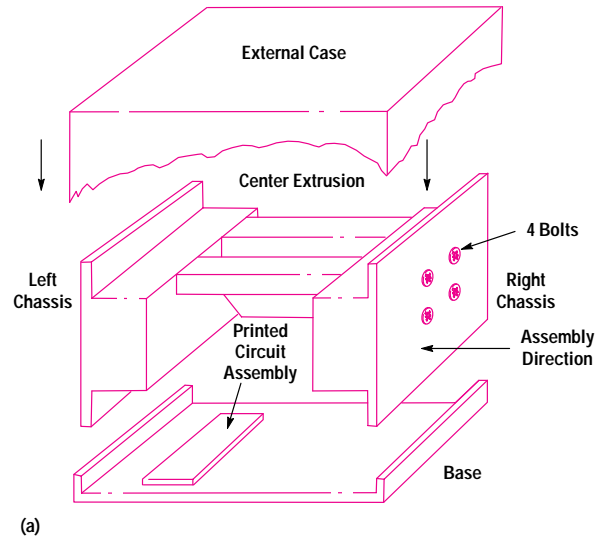


Fig. 1. The mechanical architecture of (a) the early DeskJet 1200C prototype and (b) the revised prototype and current design. Both sketches are simplified to show only the structural components. The early prototype had three structural parts which were assembled in a precision fixture with bolts from the side. The remaining parts had to conform to this structure. With this alternative, the chassis had to hold a lot of parts and they became complex. In addition, assembling the structure in a fixture entails many risks, the biggest being the difficulty of assembly in a high-volume palletized environment. Therefore the architecture was revised to be more modular (a less complex chassis) and to be capable of top-down assembly without the need for a fixture.

These considerations led to the revised prototype shown in Fig. 1b. The early prototype consisted of three structural parts joined together with eight screws. This assembly process would have been performed in a fixture. The structure would require tight tolerances, since parts assembled across the chassis (e.g., drive shafts, slider rods, and other precision sheet-metal parts) would take on their own orientation.

The revised prototype architecture moves away from requiring a special fixture for assembly. Instead, the electronic housing provides the rigid base for the structure. The right and left chassis are aligned by the sheet-metal pieces extending between them. The upper chassis is also a structural piece, forming a very rigid structure. The precision assembly is secured after the upper chassis completes the structure.

Mechanical System

Fig. 2 is an exploded view of the DeskJet 1200C printer showing the major functional areas of the mechanical system.

A nineteen-inch width was established as a goal for the product's footprint based on perceived office requirements

for a business printer. Meeting this goal also allows more efficient shipping of the product, both packaged and unpackaged. For example, using cardboard dividers, a large number of units can fit onto a pallet for shipment to distribution centers. The smaller footprint also results in lower overall costs of materials, packaging, and freight. A removable tray design contributes to smaller footprint and packaging costs.

Packaging. Requiring a printer to withstand up to 30g of acceleration is typical. But this product, with a high-volume and lower-cost market, needed a less costly (less protective) package. Through a series of mockups and cost analyses by the packaging engineer, a new target of 50g was established.

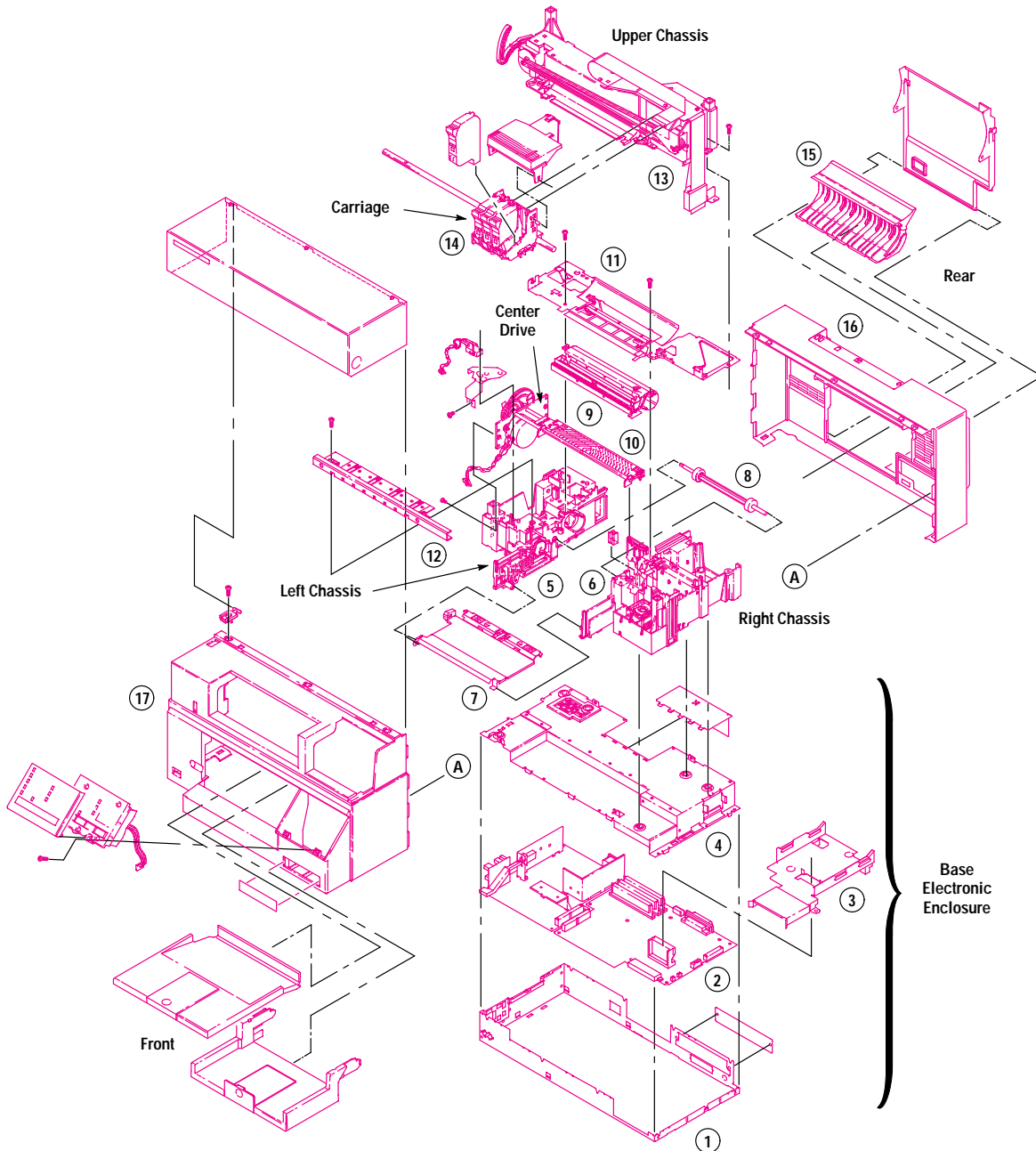


Fig. 2. Exploded view of the HP DeskJet 1200C printer showing the functional areas of the mechanical system. Major mechanical architectural subsystems include the chassis, the base, and the case assemblies. Assembly is modular and “top-down.” The top level assembly sequence is numbered.

Basically, the product is designed to be sturdy, thus requiring less protective packaging. Building a vulnerable product and then designing costly overprotective packaging to compensate would have been unacceptable. A more robust product also provides a long-term customer benefit in that it can withstand more accidental abuse over its lifetime.

The removable front tray design allows the size of the package to be reduced by 20% and also helps the product more easily achieve the 50g target.

For more discussion of the role of packaging in the product's architecture, see "Product Design Effect on Environmental Responsibility and Distribution Costs" below.

Electronics Housing. Although a full metal enclosure may appear to be an expensive solution for housing the electronics, there were several advantages in this approach. The enclosure serves as the base of the machine and facilitates assembly. It marks a first for HP in that it serves as an important structural piece of the product. The metal enclosure design easily met the ESD and RFI requirements very early in the project, thus avoiding any end-of-project modifications

that could have been costly. If the alternative approach of a sheet-metal ground plane had been used, the potential for vibration, shock, RFI, and ESD problems and associated project delays for retooling, testing, and so on would have been considerably higher.

Implementing this conservative design for the electronics housing, the project team could guarantee that only minor changes would be necessary after the lab prototype. This allowed manufacturing and tooling projects to proceed without delay and generated continuing benefits to the project.

Cabling. Cable routing within the product was considered early in the project. Using the electronics housing as a starting point, a main connector location for the cabling was established. Space throughout the product was allotted for routing the cables.

Taking a conservative approach, the project team included a sheet-metal ground plane with the trailing cable for the carriage, an area susceptible to EMI and RFI problems. Other grounding solutions were designed in with the knowledge

Product Design Effect on Environmental Responsibility and Distribution Costs

Today's cost-competitive market requires that a product design take into consideration its effect on costs in all areas of the corporation. With the early involvement of package engineering and logistics on the DeskJet 1200C printer project we were able to make visible various opportunities to reduce the cost of packaging, shipping, and warehousing, based on having a smaller and more rugged printer (and parts). By reducing the printer's size we were also able to reduce the environmental impact of packaging material disposal.

To achieve these benefits we had to meet the following objectives:

- Optimize the cost of designing a very rugged printer versus the costs associated with distributing the printer to the ultimate customer. We wanted to reduce the packaging and logistic costs which meant increasing the product strength and reducing the product size.
- Optimize the cost of designing rugged parts versus the cost to package the parts from our suppliers to the production lines. The philosophy is that the best package is no package.
- Minimize the impact of the product and parts packaging materials on the environment.
- Provide our customers with a durable printer rather than a durable package.
- Eliminate unnecessary packaging materials where ever possible.

Several key activities were necessary to meet these objectives. This is not our first product to benefit from such an approach but this time we were more diligent and coordinated about doing what was the overall right thing.

Project management supported the effort and understood the related costs. Previous projects had shown the relationship between product strength and size on the one hand, and the costs of packaging and distribution on the other. While the printer design was still in the investigation phase, the management team asked the packaging engineer to conduct a study that would help determine optimum product size and strength. The study showed we could save substantial amounts if we kept the product length under 19 inches, made the media trays customer installable, and designed a product capable of withstanding 50g shock at a velocity change of 676 cm/s.

Incoming kits of parts were created to help reduce the number of part numbers ordered, shipped, and stored. This reduced costs significantly by eliminating unneeded packaging materials for parts for the printer top case and base.

The top case kit package is reused as part of the printer product packaging. All packaging materials used to ship the top case kit into the factory are reused as part

of the package for shipping the printers to the major HP distribution centers, and then reused again as part of the individual shipping package sent to the customer.

Reusable packaging for incoming parts was implemented wherever feasible so that it could be returned to the part suppliers many times to reduce cost and trash disposal.

Setting a 50g product fragility (ruggedness) goal helped designers focus on the need to have strong products and to reduce overall costs. This enabled us to reduce the package cushioning wall thickness from three inches to two inches using low-cost molded expanded polystyrene, which resulted in a 50% reduction over an older similar-sized printer.

The design engineers understood the impact their part designs could have on the packaging costs for the printer and its parts. This resulted in a teamwork attitude; everyone shared a desire to accomplish the objectives of lowest total cost and environmentally friendly packaging.

A knowledgeable and dedicated shock and vibration champion from the design team helped keep the product designers focused on the issues that helped achieve these objectives.

Early testing on lab prototype units gave timely feedback to the designers and was done again at each build of prototype or pilot run units.

An environmentally sensitive project management coupled with HP corporate guidelines helped strengthen the objective of reducing the amount of foam cushioning, in addition to supporting the use of 25% recycled content foam at a slight additional cost.

Early involvement of packaging engineering, logistics, and environmental test engineering helped pinpoint areas of opportunity in the product and parts while the designs were still fairly flexible.

Having a dedicated project packaging engineer helped ensure that all the packaging issues were thoroughly researched from both cost and technical angles. This also gave the designers and suppliers a focal point for the evaluation of the sufficiency and cost of part and product packaging.

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that they could be taken out later if unnecessary. By not including them early, the team would have increased the risk of project delays. In fact, most of these grounding solutions were removed, reducing manufacturing cost and time.

Printing System. As mentioned previously, the main components of the printing system had been conceptualized, bread-boarded, and tested before the final architecture definition. The printing system components consist of the print cartridges, the carriage, the carriage axis (slider rod, etc.), the carriage drive (dc motor, belt, pulleys, etc.), the paper advance mechanism (stepper motor, drive shafts, and gearing system), the main heater, and the vapor removal system. The early prototypes gave us a solid understanding of the core or heart of the machine and the remaining product functionality was built upon this foundation.

Early in the project, the target specification for throughput was upgraded to seven pages per minute. Furthermore, the paper path had to be reliable, defined as fewer than approximately one misfeed per thousand feeds.

Printer throughput is a composite of pick time, feed distance, deskew, final feed and print, and paper eject. Although early development had focused on using a single motor to drive all of these subfunctions, the resulting print speed of four pages per minute was judged unacceptable. The design risk (and related project delays) of pushing the performance of the single motor any more was too great.

The project team decided to employ an additional motor dedicated to sheet feeding. This motor provides two functions that were previously handled by the other two motors in the product. These functions are to drive the automatic sheet-feed mechanism to pick a sheet off a stack of paper residing in the machine and to feed or move this sheet to the printing area where the primary paper advance mechanism takes over to print on the sheet.

The additional motor accomplished several things. First, the throughput is improved considerably. In the high-speed text mode of printing, throughput went from around four pages per minute to around seven pages per minute. This is possible because of the cueing-up capability the product now has. While one sheet is being printed, another can be picked and fed.

Another advantage of the additional motor is design simplification. By having a dedicated motor for sheet feeding, the mechanisms and algorithms previously required with only two motors in the product were simplified significantly. This gave the design team more design flexibility and lowered the overall design risk.

The product architects spent a great deal of time debating the trade-offs associated with the various media paths possible. Fig. 3 shows three of the fundamental paths. Because the media path chosen affects the product footprint, customer interfaces, ability to handle different types of media, and functionality of the product, this issue was analyzed at length.

Fig. 4 shows the media path ultimately chosen. It has a main input tray capable of automatically feeding sheets positioned in the front of the machine under the output tray. This is a configuration used in other HP printers of similar type and is

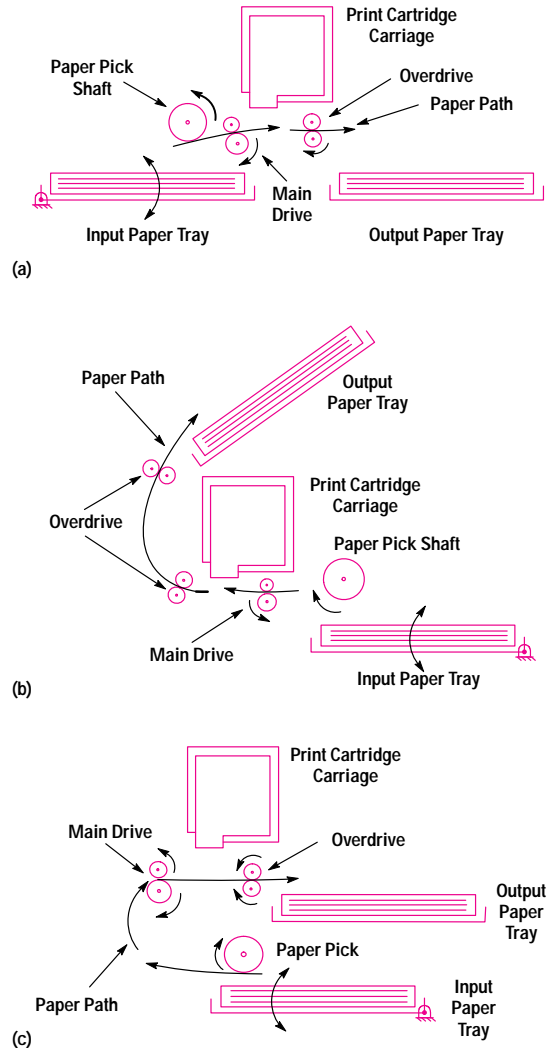


Fig. 3. Media path alternatives and basic product architectures. In the simplest architecture (a) the media path is flat. No bending of the media makes it easier to print on specialty stock such as envelopes. The biggest advantage is speed because the media path is short. However, the footprint is large. Alternative (b) is essentially the LaserJet architecture. It has a smaller footprint than (a), but requires an additional set of drive rollers, a cost increase. Output is ink side down, which poses some engineering risk. Alternative (c) has a smaller footprint than (a), does not require additional rollers like (b), and output is ink side up. However, there is a large media bend; stiff cards and envelopes would be difficult to feed.

well-accepted by customers. An additional manual feed slot is designed into the top of the product for handling individually loaded media types.

The DeskJet 1200C dual media path handles a wide variety of media types, including English and metric letter sizes (A, A4, and legal sizes), plain paper in a variety of grades, several sizes of envelopes, transparencies, special HP paper for improved graphics quality, glossy media for improved graphics quality, and label stock. Plain paper, transparencies, special paper, and glossy media can all be automatically fed from the main input tray. Label stock and envelopes must be individually loaded in the manual feed slot. The manual feed slot will accommodate all of the media types provided they are individually loaded.

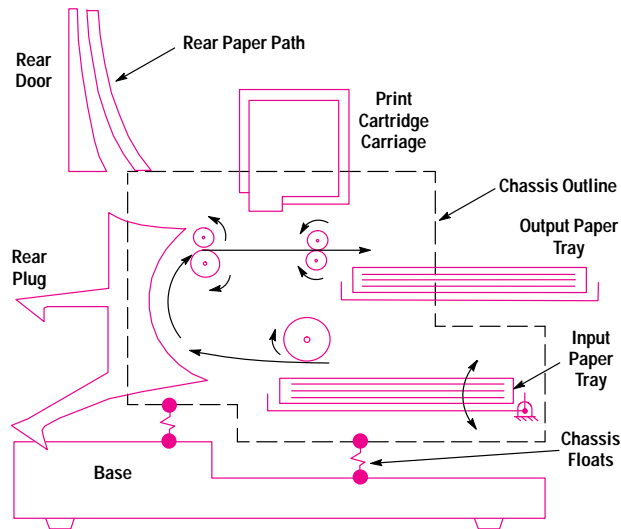


Fig. 4. The dual media path of the DeskJet 1200C printer is an enhanced version of Fig. 3c. It has a small footprint and low cost. Speed is not optimized but is acceptable. A rear media path that doesn't bend the media so much is added for specialty items such as envelopes, cards, and labels. The media path and print zone are aligned with the chassis and float on top of the base.

Other design features of the media path are widgets that hold the media flat in the print zone and automatically adjust depending on the media size placed in the main input tray, and customer-installable input and output trays that reduce the product size for more efficient packaging and shipping.

Another consideration in the media path design was how to handle the unlikely event of a media jam. The media path shown in Fig. 3a has a serious limitation in this regard. The media feed slot from the input tray to the print zone is not easily accessible for clearing media jams. In addition, the manual feed path would have a similar limitation. To address this need, a rear door is designed into the rear case of the DeskJet 1200C in conjunction with a removable part called the plug. The rear door and plug provide an effective way of accessing both media paths for jam clearance. An interesting feature of this design is that, by opening the rear door, removing the plug, and removing a metal cover, the customer gains access to the product's single inline memory modules (SIMMs) for upgrading memory or installing the PostScript language.

A final jam clearance feature consists of a pinchwheel release mechanism activated by opening the front door. This feature makes media caught in the printing area of the product easy to remove.

Airflow Considerations. In laying out the DeskJet 1200C architecture, special provisions had to be made for airflow. To keep costs low, the project team decided to use a single fan to accomplish the tasks of heat dissipation and vapor removal.

Cooling the power supply board became a major consideration. The 180-watt supply runs at 140 watts steady-state with an efficiency of approximately 70%. This means that there are about 40 watts of heat to dissipate. Several power supply

vendors recommend that to cool a power supply of that size, a minimum airflow rate of 20 ft³/min is required.

Initial testing of a mockup indicated that with a single fan we would only have about 8 ft³/min. The team decided to take parallel paths, that is, pursuing the single-fan option and leaving the option of a second fan open by including the required support. Space for the second fan was included in the left chassis and additional grills were added. At the same time, the cooling airflow was designed to move directly across the power supply area and the board layout was optimized to best use the available airflow to cool the critical components. A few iterations resulted in a design that has ample thermal margin with less than half the original conservative airflow estimate. The additional grills are still there, unused, in the final product.

The second requirement of the fan system is to remove excess vapor from the writing area and excess vapor and heat from the heater enclosure. To accomplish this, a manifold was designed to sit directly behind the print cartridges, extending the full width of the writing area. This design also pulls air from the heater enclosure.

During development, many of the variables that affect the airflow were changing. We had not selected a fan supplier and wanted to keep that selection open. The print cartridges and the heater system were also under development so the actual requirements were still unknown. To meet these changing requirements, a simple wall was designed into the vapor removal snout that would allow the system to be tuned to any combination of fan supplier, print cartridge design, and heater design.

Filtering was another consideration for the airflow system and planning ahead allowed an optimal system to be designed and implemented. Fig. 5 shows the airflow paths in the DeskJet 1200C.

Manufacturing Considerations. As explained earlier, the product architecture changed from the early prototype to a revised prototype (see Fig. 1). This was partly because of a desire for a lower-risk permanent tooling set. Splitting the two plastic structural pieces into three helped reduce part complexity which made the tools easier to debug. A two-piece enclosure with a front and rear case as opposed to a single-piece, over-the-top enclosure also made the tooling easier to put together.

Extensive use of rapid prototyped parts also smoothed the tooling debug phase because our designs were more complete before releasing for tooling.

The design team stressed the use of sheet metal, which allows quick prototype turnaround. The team was trained and understood that product forecast volumes were high enough to support tooling (i.e., progressive dies) of sheet-metal parts.

Architecture redefinition from the early to the revised prototypes was also driven by assembly requirements. Table I demonstrates the effect of the improved product architecture on assembly. Typically, as the product design moves through successive prototype phases, more functionality is added and schedules are tightened at the expense of assembly performance. In this case, however, the part count and

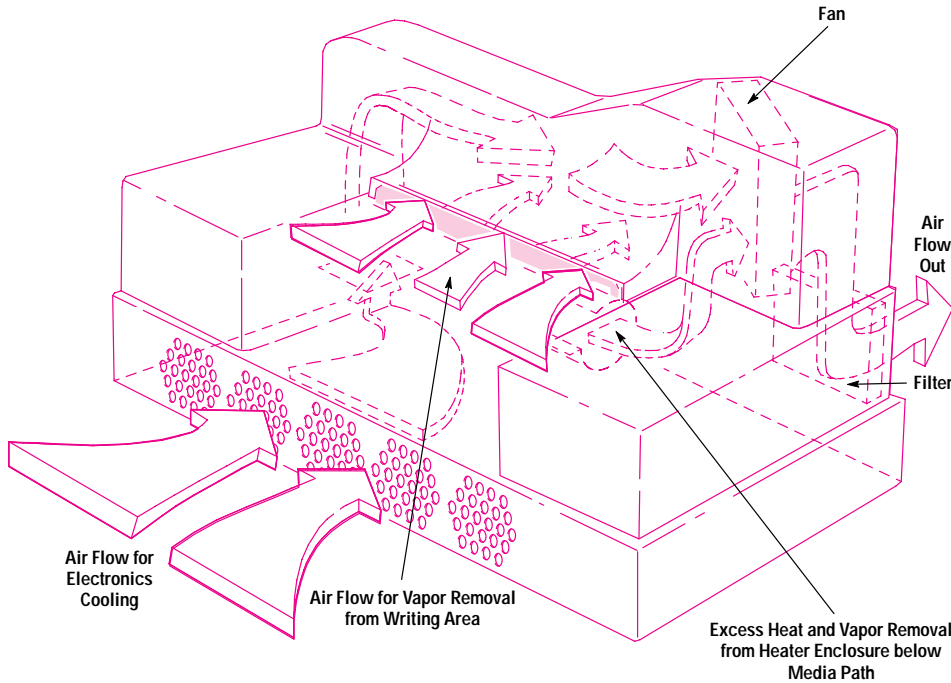


Fig. 5. Airflow paths through the DeskJet 1200C printer.

assembly efficiency improved even while the overall product functionality (P_{min}) increased.

Product architecture development from the early to the revised prototypes enabled the design team to identify areas of

opportunity within the product where a design for assembly impact could be realized. This gave the design engineers an early start addressing areas needing attention. Major improvements were made in the service station, the main heater, and the upper chassis assembly. The design team practiced design for assembly on a case-by-case basis. The cost trade-off between part material and assembly content was quantified early in the prototype phase for making design decisions. The team used general design for assembly guidelines, but engineers did not feel constrained by the rules. The DeskJet 1200C turned out to be a product with many simple and clever assemblies that do not require fixturing or reorienting of the product during assembly.

Early involvement in assembly also generated a wealth of accurate information to help drive the factory design. For example, subassemblies were identified well before product introduction. For another example, assembly of printed circuit boards into the product and the electronic enclosure requires 23 screws. Since this was apparent in the revised prototype architecture, which represented the final product, the team could go ahead and begin looking at ways to handle a very large number of screws.

Electrical System

The DeskJet 1200C electrical block diagram, Fig. 6, shows the relationship between the major functional areas. The electronics were designed with high performance in mind at the start. The system uses a single processor with one major support ASIC (application-specific integrated circuit) and three minor support ASICs, one for the processor and two for firing the print cartridges.

The Intel 80960SA processor is a RISC (reduced instruction set computing) machine designed to execute instructions in fewer clock cycles than conventional processors, thereby improving performance. To help with the multiple and parallel functions needed to make the printer operate, a 208-pin custom ASIC is employed. This ASIC shares the address and data bus with the processor and controls a portion of the

Table I
Assembly Performance of Early and Revised Prototypes
(Projected revised prototype shown for comparison.)

| | Early Prototype | Projected Prototype* | Revised Prototype |
|---|-----------------|----------------------|-------------------|
| Total Part Count | 220 | 265 | 214 |
| P_{min} (Theoretical minimum number of parts or preassembled items)** | 100 | 125 | 129 |
| Assembly Efficiency*** | 13% | 13% | 18% |
| Difficult-to-Assemble Parts or Subassemblies | 50 | 60 | 35 |
| Number of Screws | 43 | 65 | 62 |
| Number of Different Screws | 10 | 15 | 9 |

* Prototype evaluations based on either actual parts or 3D models using Boothroyd and Dewhurst method.¹

** P_{min}^1 is a measure of the complexity of the product. In general, the more functionality there is in the product, the higher the P_{min} value.

*** Assembly efficiency (AE) is a ratio of the theoretical minimum number of parts (P_{min}) to the estimated assembly time. An approximation is used to compute AE (2.933 seconds per part), so AE values are used for relative comparisons only.

$$AE = \frac{P_{min}}{P_{total}} \times \frac{T_{min}}{T_{total}}$$

or, assuming that $T_{min}/P_{total} \approx 2.933$ seconds/part,

$$AE = 2.933 \text{ seconds/part} \times \frac{P_{min}}{T_{total}}$$

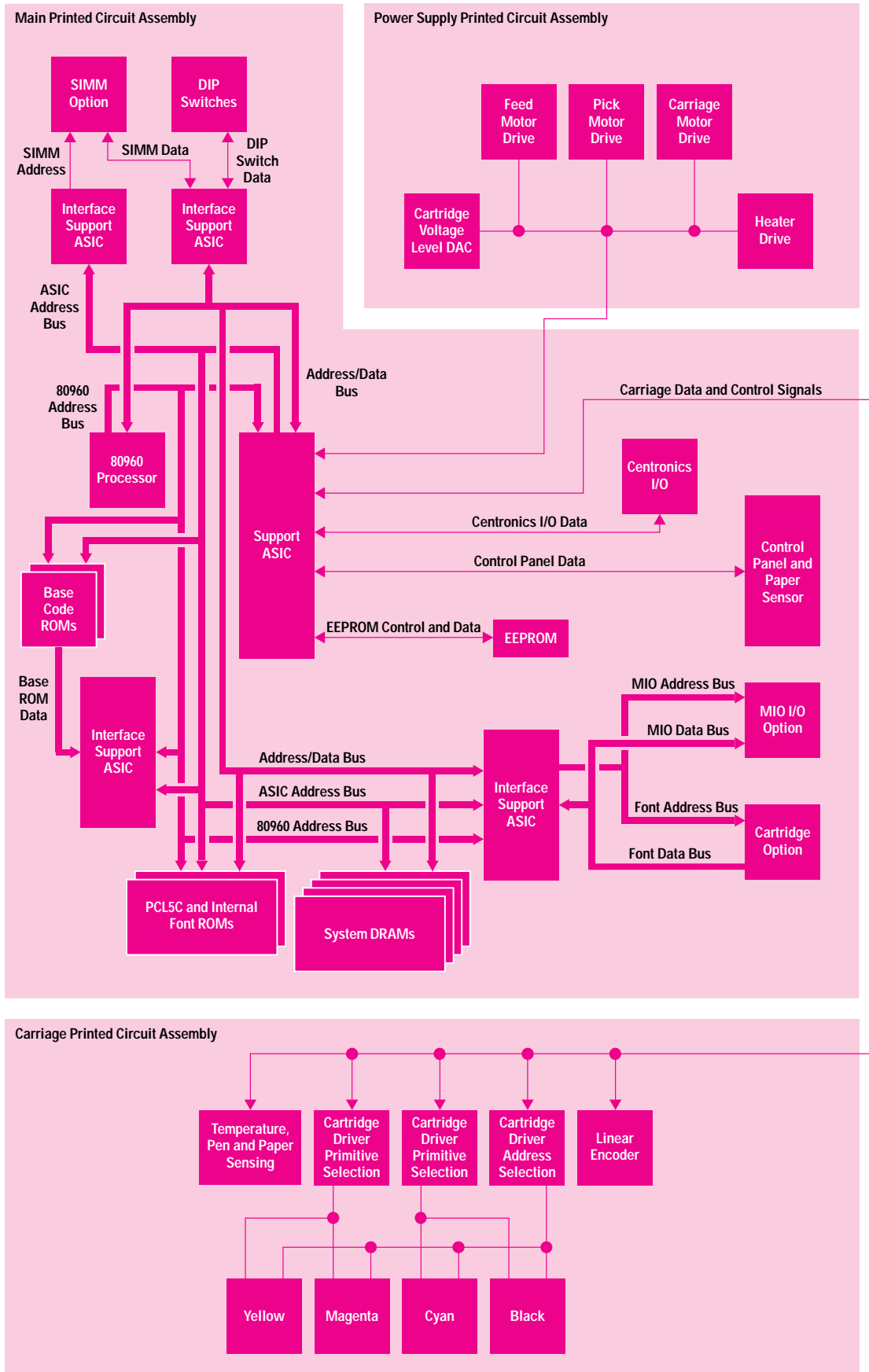


Fig. 6. Simplified electrical system block diagram of the DeskJet 1200C printer.

address bus. This ASIC handles all of the motion control, print cartridge firing, I/O, decoding, sensors, control panel, heater control, EEROM access, DRAM control, and various firmware aids.

The motion is controlled with three motors: a dc motor, a unipolar stepper motor, and a bipolar stepper motor. The dc motor controls the carriage motion and is a closed-loop design with a linear encoder for feedback. This motor uses two pulse width modulated signals to determine drive strength and direction. The bipolar stepper controls the paper movement during printing. This stepper is a two-phase design with a current control for accurate movement. The unipolar stepper is used to pick the paper from the tray and is an open-loop design. The two stepper motors are independently controlled.

The standard I/O is Centronics with the ability to expand to any available I/O through a modular I/O port (HP MIO system). The HP MIO interface is an HP-developed standard interface. The MIO port communicates through one of the minor support ASICs, which is shared with a font cartridge option. This ASIC handles both address and data buses.

The on-board memory consists of six areas: base code, language code, fonts, DRAM, EEROM (electrically erasable read-only memory), and expandable. The base code is split between two 500K-byte devices and uses one of the minor support ASICs to interface with the data bus. Its two functions are to help ease bus loading and to provide a small pipeline. The language code uses a single 2M-byte read-only-memory (ROM) which contains the PCL 5C language and several internal demonstration plots. The fonts are also contained in a single 2M-byte ROM. The main DRAM is used for swath and processor scratch memory. The PCL 5C ROM, the font ROM, and the DRAM have direct access to the address and data bus. The EEROM stores constants that must be retained when the unit is powered off. Finally, the expandable space can be used for up to 24M bytes of DRAM, or up to 18M bytes with the PostScript option. This expandable area consists of three industry-standard 72-pin SIMMs. All of the expandable electronics communicate with the main system through two minor support ASICs, one handling the address bus and the other the data bus.

Three driver ASICs control the needed energies and select the individual nozzles for firing the print cartridges. Each print cartridge can be treated as a matrix of 104 locations. To reduce conductor count, the black cartridge is multiplexed with the cyan and the yellow with the magenta. One ASIC selects the column and the other two select the print cartridge and the row. It is possible to fire up to eight nozzles of a given print cartridge simultaneously with this design.

The paper edge sensor can detect either paper or transparency media, using light-scattering properties to distinguish one from the other.

Firmware System

Because of the performance and throughput requirements, a new firmware architecture was developed for the DeskJet 1200C printer. Among these requirements were:

- PostScript and PCL 5C concurrent on the same machine

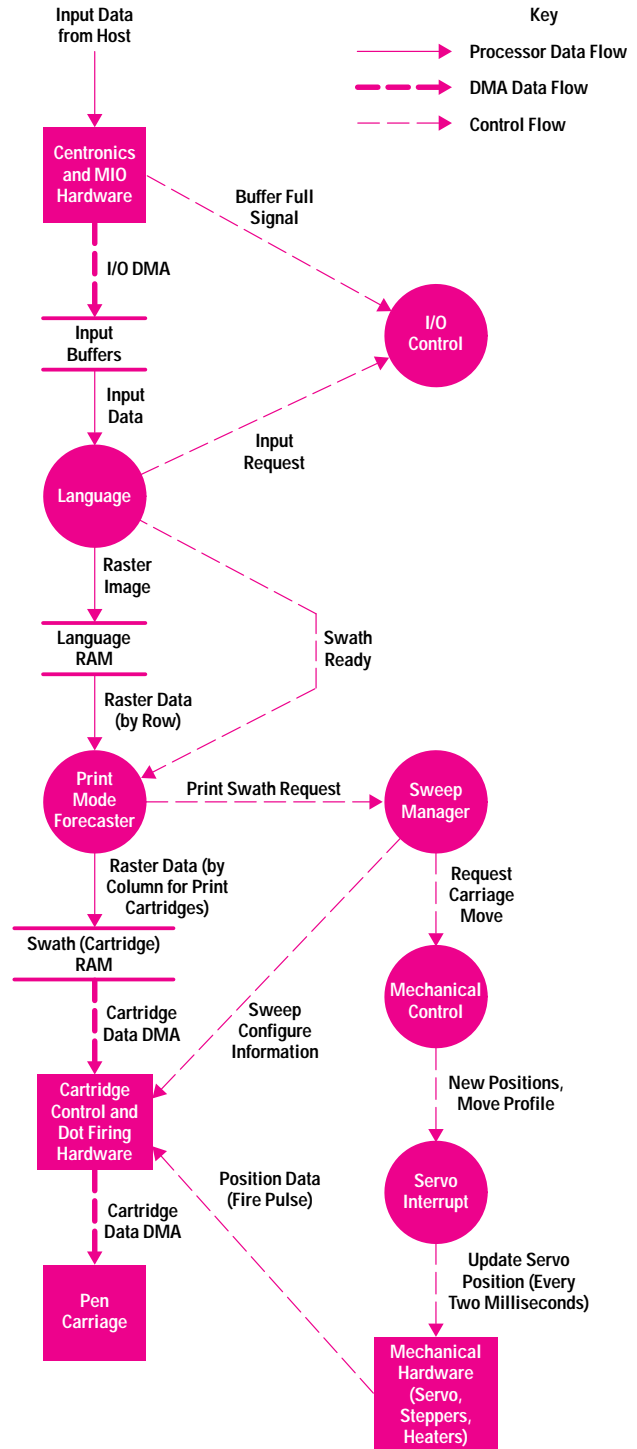


Fig. 7. DeskJet 1200C firmware overview.

- Four independent 104-nozzle print cartridges
- Text printing at six pages per minute
- Full color graphics printing at two minutes per page
- Centronics and MIO connectivity
- HP LaserJet printer compatibility
- Three motion control systems, two heaters, and a blower
- HP Resolution Enhancement technology (RET).

Fig. 7 gives an overview of the DeskJet 1200C firmware.

(continued on page 66)

A New Product Development Model

In the traditional Hewlett-Packard product development approach, a new product is conceived in the research and development lab with input from marketing. During this investigation phase all new technologies are proven out.

Once this phase is complete, the next phase builds several prototype runs of varying quantities to demonstrate the capabilities of the product. Manufacturing engineering begins to participate with the design team to ensure that the vendors are HP-approved and that the materials and components selected are acceptable for production use.

Next the tooling strategy is defined and the product begins to take its final shape. Most vendors have been qualified by the end of this stage and the manufacturing team begins to determine how this product will be manufactured and shipped.

Production line personnel are beginning to be assigned for the new product line and the industrial engineers begin the production line layout. When production starts, the product is placed in the capable hands of the production engineers to begin producing products for the field.

The R&D team, its work now complete, is reassigned to new projects, and for them the cycle begins anew. The manufacturing and production teams now own the designs and ensure that all part specifications and drawings are complete and that the product can be built. The initial ramp is often a bit rocky, but in a short period of time, products are being produced in quantity.

Much of the role of the manufacturing team in this scenario is to police the R&D team. They are there to ensure that the R&D team delivers a solution that can be manufactured. They make sure that the specifications are all stated and correct, that drawings conform to manufacturing specifications, and that the components and materials selected all meet corporate standards. They make sure that the product can be built on the production line being built by the industrial engineers. They ensure that there is quality in the product by designing production line tests or audits.

This is not a very rewarding position to be in. These engineers are not responsible for the product's design, but when the production point is reached, it is their product. The R&D team is gone and the success of the product rests on their shoulders. This puts them in a position of not wanting to take any extra risk above the normal. It also slows the communication path from designer to vendor because there is always someone in the middle who needs to share the information with both parties. Also, it is very difficult to make changes during the production ramp because the manufacturing engineers do not have the same knowledge base as the original designers and so changes entail more risk.

DeskJet 1200C Product Development Model

In the early phases of the DeskJet 1200C project we came to the realization that the traditional product development cycle was not going to work. This product was expected to be the highest-volume product ever produced at the San Diego Printer Division. We understood the strain that it would place on the manufacturing organization to have a product of this volume and complexity suddenly handed over to them. We were also feeling the cost pressures that are typical of a competitive environment and did not feel that we could staff the project with extra people. We realized some of the shortcomings of the original model such as the communication path to the vendor, the lack of product knowledge during the ramp, and the lack of manufacturing experience on the part of the R&D designers. From this came a new concept of product development that became known as the "new model."

The new model addresses some of the shortcomings of the original product development model. Deep in the investigation phase, we staffed the product development team for success. We brought process engineers, quality engineers, and

materials experts onto the project from the start. We also had purchasing people with us right away. Another focus was to have all the engineers, managers, and buyers sitting together in one location. This may sound obvious, but until then, many manufacturing engineers and buyers did not sit with the project personnel. We then stripped the various titles and everyone became an "engineer." With this change came job responsibility changes. All engineers were responsible for the design, specification, and production of their own parts. No longer was there someone in the middle to work through to get to the vendor; the engineers called them directly. No longer was there a police function to ensure that you were following the rules and releasing all the drawings. No longer would someone else design tooling to enable the product to be assembled. That was now each engineer's responsibility.

How could the R&D engineers be expected to be responsible for all these tasks, many of which they knew nothing about? As mentioned above, we staffed with a few experts. One of the first tasks for the experts was to distribute their knowledge to the rest of the engineering team. Metals engineers taught the others about metal design. Plastics engineers did the same for plastics. In return for this training, the R&D engineers taught the experts about part design. Each process engineer had now also become a design engineer. Success was possible only through each engineer's taking full responsibility for a particular design from concept through production.

Benefits of the New Model

What were the benefits of this approach? Many. Out of this design approach, a better product was developed. As this article is being written, we are in our fifth month of production ramp. The product has met almost all of the quality and reliability objectives as well as the manufacturing goals for cycle time and volume. The engineers feel rewarded by successfully taking parts from concept to production. No longer did we cast the manufacturing engineers first in a police role and then in the role of producing something designed by someone else. Instead we had a design team of solid engineers that stayed with the product through the ramp and into stable production. We also believe that we were able to achieve a shorter cycle time for lower cost at each phase by having everyone with part responsibility directly involved with the vendors.

Open Issues

This change was not without challenges. We still have issues about the long-term support of the vendor base and product line. Who will manage the vendors when the rest of the engineers destaff the project and return to R&D? We also still need an expert base. In the beginning, we staffed with several experts. If you make everyone a generalist, how do you grow experts in leading-edge technology?

Conclusion

Building on past projects and adjusting the product development process to new realities in the marketplace and new manufacturing techniques, the DeskJet 1200C project team adopted a flexible, fast-moving organizational structure in bringing the printer from the drawing board to physical reality. The process included a heavy dose of common sense. Some of the ideas were not revolutionary, but simply made a lot of sense. What was revolutionary was that we could break the traditional paradigm of product development that spanned several functional areas, develop better engineers with greater breadth, and produce a remarkable new printer that has already contributed to a redefinition of printing in the mainstream office.

Anton Tabar
Kevin Bockman
Project Managers
San Diego Printer Division

The first major decision was to implement a multitasking operating system to allow multiple independent self-contained processes to run on the single 80960 processor. Up to 12 tasks can run concurrently, ranging from rendering a PCL 5C image to controlling the sensors. A single-threaded operating system would have not met the time-slicing demands that were placed on the system. The overhead cost of implementing the operating system is about 7% of the overall time, but it reduced development and support time because of the independence of the tasks. It also allows the PCL 5C language to become dual-threaded which in turn allows it to begin formatting the next page while the previous page is being printed. This is critical to meeting the text and graphics throughput requirements.

The second major decision was to implement a language independent interface to the print engine. Traditionally, our print engines were tightly coupled with the language system. Because of the need to support PostScript as well as PCL 5C as native on the printer, a technique was required for both languages to communicate with the print engine in an independent way. This allowed concurrent development of both PostScript and PCL 5C so that they could be introduced simultaneously. It also permits a high level of language code reuse on different products. This language independent interface has now been implemented successfully in three printers and is described in the article on page NO TAG.

To meet the needs of the mainstream office, the interface to the computer world needed to be flexible. The unit is shipped with a built-in high-speed Centronics interface that is expected to meet most of the needs of the IBM-compatible PC world. To meet the needs of other computing platforms and interface technologies, an HP MIO port was also added. This MIO port implements version 5.0 of this HP standard interface. For operation in mixed environments, the system implements "hot" I/O switching. After the end of a job or after a specified amount of time with no activity, the processor releases the active port and begins polling for I/O requests from both ports. Once I/O is detected, the inactive port is blocked and data is received from the active port.

The last major design decision is the implementation of a print mode forecaster to help meet the throughput requirements. The print mode forecaster looks at the next 2/3 inch and determines from the data whether to print in one pass or three passes. It also predicts the most intelligent paper movement so that the maximum amount of data can be printed at one time without compromising the quality of the print (for example, the forecaster never splits text or graphics in the high-quality mode). It is the responsibility of the

forecaster to pick the optimum motion path for both vertical and horizontal movements. It also manages swath RAM and controls the Resolution Enhancement technology (RET) that is implemented in the hardware. This is a very complex module consisting of approximately 7000 lines of code.

Conclusion

Given the challenges of media independence, speed, print quality, low cost, and a fast development cycle, the DeskJet 1200C team used the new seamless engineering model and concentrated on doing a thorough job from the beginning. This allowed all of the major areas—mechanical, electrical, and computer—to architect a system with the flexibility and margins to meet its goals.

Acknowledgments

A program of this size had many contributors. We would like to thank all those who contributed to its success. There are far too many to name and many have been named in other articles. We would especially like to thank the following: Bill Hilliard for the firmware architecture and tremendous firmware support for the rest of the project, Mike Harless for the I/O firmware, Gary Gragg for the product diagnostics and the manufacturing line tests, Steve Mueller for his PostScript contributions, Jeff Sunamoto for his commitment and technical breadth, Cary Enslow for the mechanical, Graciela Gomez for the electrical, and Toby Cowger for the firmware designs on the front panel, Steve Hendricks for the electronics sheet-metal enclosure, Ron Kaplan for the product enclosure, Dick Kemplin for his innovative chassis design, Bill Meyer, John Thomas, and Bob Haselby for their design and management of the analog portions of the electronics and sensors, Tim McDonough and Phil Schultz for the digital design portion of the project, Joe Fiske for his communication support between the DeskJet 1200C work team and the engineering staff, Jim Ruder and Phil Faraci who played key roles in the definition of the new product development model, and Oscar Padilla for creating many of the sketches used in this article. Special thanks go to the DeskJet 1200C work team without whose diligence and support we would not be producing products today, and to Tao Ngo who lent his technical support throughout the project.

Reference

1. G. Boothroyd and P. Dewhurst, *Product Design for Assembly*, Boothroyd Dewhurst, Inc., 1991.

PostScript is a trademark of Adobe Systems Incorporated which may be registered in certain jurisdictions.

Print Cartridge Fixturing and Maintenance in the HP DeskJet 1200C Printer

The carriage assembly locates and transports the four print cartridges precisely. The service station provides capping, wiping, and priming functions for print cartridge maintenance and recovery.

by Michael T. Dangelo, Reza Movaghar, and Arthur K. Wilson

One of the main goals for the HP DeskJet 1200C printer was a narrow footprint so that the printer could be placed on a desk or existing desk stand. To achieve this goal, the carriage assembly and print cartridges are designed for minimum space between parts and for minimum overall width.

The overall width of the printer is dependent on the width of the paper plus two times the width of the carriage assembly. This is necessary to allow all of the print cartridges to print to the edge margin of the paper on each side.

The compact design makes it possible to register the four print cartridges accurately with respect to each other and with respect to the paper to ensure high print quality and high definition.

Design for manufacturing and assembly was considered from the beginning of the project. Areas of importance were low part count, modular construction, no adjustments, and ease of assembly. All parts either snap on, are nested inside other parts, or are held on with a minimum number of fasteners. The carriage assembly is modular in construction which allows subassemblies to be built and tested before being installed on the carriage.

Carriage Assembly Description

The HP DeskJet 1200C printer carriage assembly is built around a single-piece print cartridge housing, with all other assemblies and parts attaching to it. The carriage assembly includes a modular interconnect assembly, a paper sensor assembly, print cartridge bias and loading springs, slider rod bushings and preload pads, and the cover/trailing cable assembly, as shown in Fig. 1.

Print Cartridge Housing and Parts

The one-piece approach was taken to minimize tolerance buildups, maximize stiffness, and lower cost. This approach does have its drawbacks, however. To get a complex-shaped one-piece part with many features on all surfaces requires a very intricate and complex plastic injection molding tool.

To ensure the closest possible alignment of the print cartridges, the print cartridge datums in the print cartridge housing are machined relative to the slider rod axis to match actual operating conditions.

The print cartridges are located in the housing with biasing springs that push the print cartridges into position against the datums. Three sets of springs are used for biasing the print cartridges in the three respective axes. Of particular interest is the Z bias spring, which serves several functions. It pushes the print cartridge down to the bottom of the housing (Z direction), it clamps the top of the print cartridge in the housing, and it pushes the top of the print cartridge in the X direction against the X stops. The spring assembly nests in the housing and is held in place by the interconnect assembly.

Attached to the side of the print cartridge housing is the paper sensor. This is used to tell where the edge of the paper is and identify whether paper or transparency media is being used. The sensor assembly snaps onto the housing and plugs into the interconnect assembly.

The slider rod bushings, slide pads, and preload pads all snap or slide onto the housing and require no other attachment.

Interconnect Assembly

The interconnect assembly (Fig. 2) is modular in construction and is installed in the print cartridge housing as a complete unit. The backbone of the interconnect assembly is a one-piece frame with alignment pins and holes for obtaining proper alignment of parts and for positioning in the print cartridge housing.

Attached to the frame is a one-piece flexible circuit that makes electrical contact with all four print cartridges and with the carriage print cartridge driver board (carriage board).

The flexible circuit interconnect pads are positioned against the print cartridge contacts with an elastomeric pad. This pad is backed up with a spring-loaded plate, which supplies the force required for electrical interconnect. This system allows a long interconnect distance and also gimbals to align the face of the interconnect with the print cartridge contacts.

Also included in the frame are encoder strip guides. These guides align the encoder strip to an encoder for determining carriage position and velocity, which is attached to the carriage board.

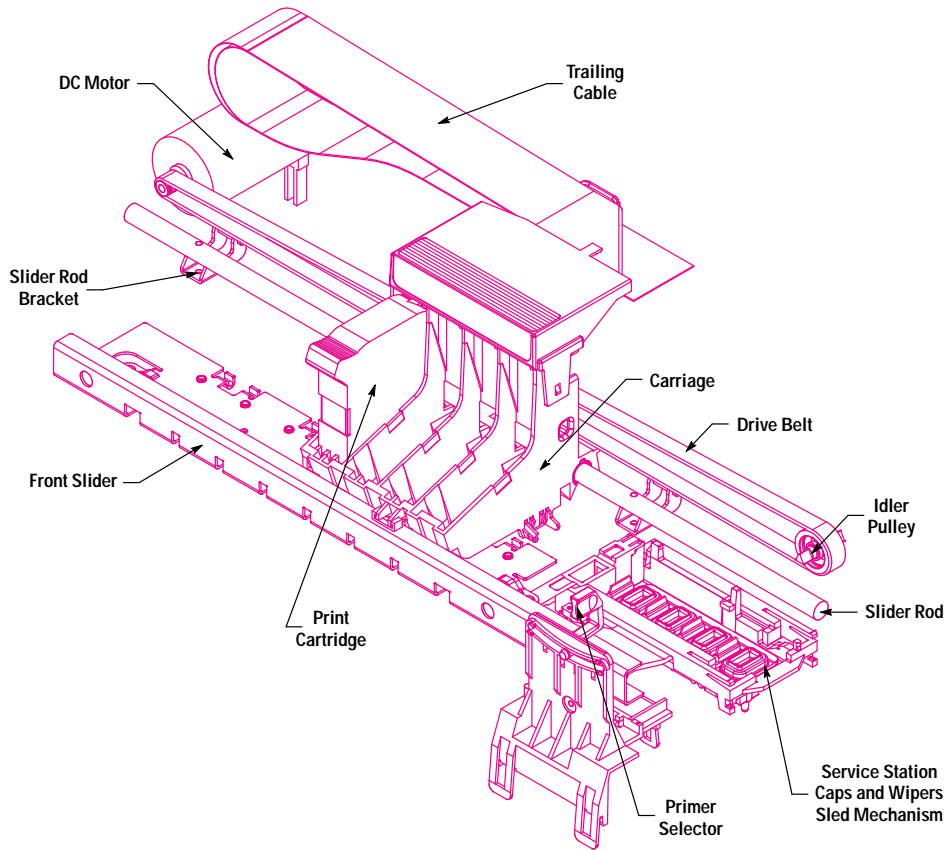


Fig. 1. Isometric view of the DeskJet 1200C carriage assembly: the carriage with a print cartridge, the carriage drive and support, and the service station.

The carriage board has a number of functions, the primary one being to drive the print cartridges. On this board are the encoder, connectors for the trailing cable and paper sensor, and electrical interconnect pads for connection to the flexible circuit.

Pressure is used for the electrical interconnect of the carriage board to the flexible circuit. An elastomer strip is nested in the frame and forces the flexible circuit against the carriage board contact pads. The carriage board is clamped to the frame along the contact area with three screws.

The carriage board is aligned to the frame and flexible circuit with two locating pins. This provides for proper positioning of the flexible circuit to the carriage board and aligns the

encoder in the frame. The carriage board is positioned vertically in the carriage assembly. This allows the trailing cable to attach directly to the top of the board using minimum space.

The interconnect assembly is positioned in the carriage by two pins and the center print cartridge wall. It holds the print cartridge clamp spring in place and positions the print cartridge interconnect circuit. The complete module is held in the carriage assembly with one screw.

A cover that snaps onto the carriage protects the print cartridge clamp spring, positions the trailing cable, and hides electrical components from view.

Carriage Axis

In the DeskJet 1200C printer, the black and color dots are laid down on the media by a scanning printhead. A well-supported and controlled print cartridge carriage axis is essential for accurate dot placement and optimum print quality. The distance between the printhead and the media is another important variable in print quality and has to be set nominally within small tolerances. This has to be achieved by simple adjustment within a few seconds. The scanning head also determines the footprint and compactness of the print engine, which affects the desktop nature of the product and the shipping cost. Low cost is the major constraint imposed by high-volume requirements.

A two-dimensional side view of the carriage axis and drive is shown in Fig. 3. A linear encoder with a resolution of 150 lines per inch determines the absolute position of the printhead. Servo control of the carriage is based on the quadrature output (4×150 counts) of the optical encoder, and is updated every 0.002 second. A state-space model was developed using

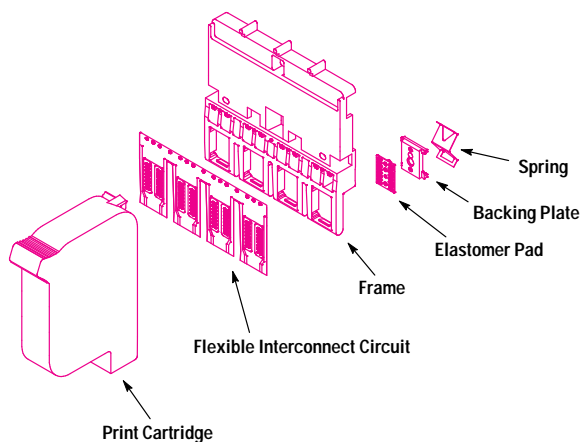


Fig. 2. Print cartridge interconnect assembly.

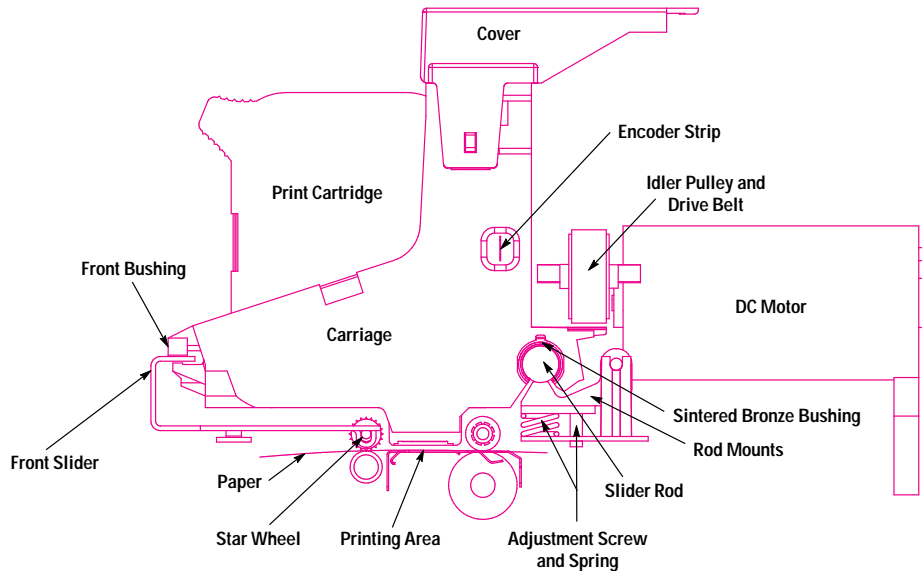


Fig. 3. Side view of the carriage axis.

the MATLAB software package to simulate the open-loop and closed-loop behavior of the dynamic system. Real position and estimated velocity feedbacks are optimized for maximum velocity stability (i.e., velocity variation $\leq 5\%$ of slewing speed) as a function of carriage mass. The mass of an empty carriage is 36% of the mass of a carriage with four full cartridges.

As shown in Fig. 3, the encoder strip, print cartridge nozzles, slider rod, and timing belt are located close to each other to minimize the vibrations of the carriage both in rigid and non-rigid mode. The carriage is supported in front by a sheet-metal piece called the front slider which is also a functional part of the media axis and holds eight star wheels to control the media path. The sliding surfaces are a molded acetyl piece on the carriage and a polyethylene tape on the front slider. These two surfaces reduce the friction, noise, and wear considerably. The friction reduction in the front reduces vibrations caused by this force. The only slider rod in the machine is 3/8 inch in diameter and is supported at two midpoints by two identical stamped sheet-metal parts called rod mounts. The midpoint supports have several advantages: small rod diameter, high natural frequency, small footprint, and ease of print-cartridge-to-paper height adjustment.

The rod mounts rest on two compression springs. Two tap-tight screws hold the mounts against the springs, going through a sheet-metal part sandwiched between the top and lower chassis. These two adjustment screws control the print-cartridge-to-paper height. The height adjustment is done at the assembly line. The print cartridge gauge is inserted in the black stall of the carriage for height adjustment to maximize the text print quality.

The main bushings are two split C shapes made of powdered sintered bronze with impregnated oil. This type of bushing has good friction characteristics and is very cost-effective. The rotational dynamics and chatter effect of the carriage in unidirectional and bidirectional printing are minimized by a preload bushing and spring that bias the carriage with respect to the slider rod, as shown in Fig. 4.

The carriage is driven by a direct-drive dc motor through a tensioned timing belt. The dc motor and tensioner are part of the upper chassis of the printer. The carriage trailing

cable rests on the upper chassis and sweeps in a minimum space between the top case and the upper chassis.

Service Station

Inkjet technology has come a long way since 1984, from the first printhead with twelve nozzles to the current 104-nozzle DeskJet 1200C printhead, but one thing has remained a struggle: maintaining a clean nozzle plate. Nozzle plates tend to crust externally with everything from dried ink to paper fibers. Nozzle plates tend to crust internally with everything from ingested paper fibers to dried ink. The challenge of the service station engineer is to keep the external surface of the nozzle plate clean with a minimum of hardware (wipers, caps, etc.), and to provide a fairly painless method of correcting a printhead that has succumbed to external or internal contaminants (priming, spitting, pulse warming). Thus the challenge includes both preventive maintenance and recovery. Fig. 5 shows the DeskJet 1200C service station.

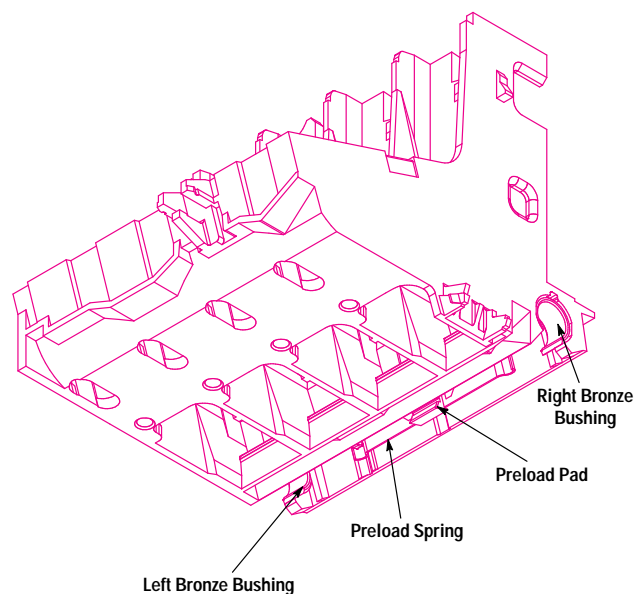


Fig. 4. Bottom view of the carriage, showing antichatter bushing and spring.

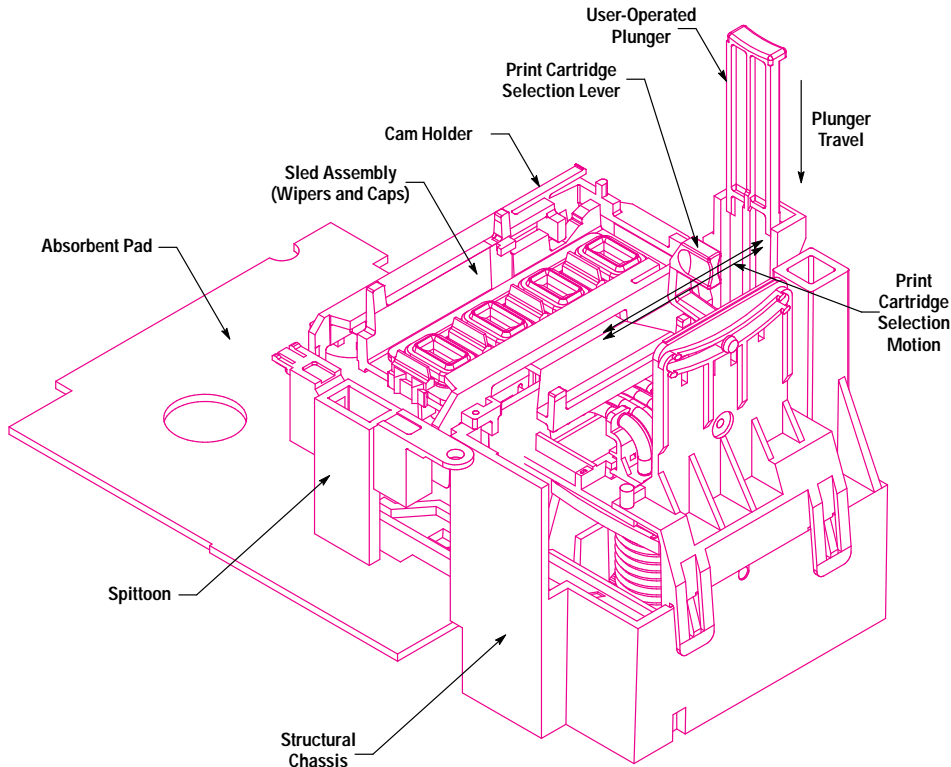


Fig. 5. Isometric view of the service station.

The key components of a thermal inkjet service station are the cap, wiper, primer, and associated mechanisms that allow these components to interact with a printhead.

Cap. To prevent the printhead from drying out when not in use it needs to be stored in a high-humidity sealed chamber. The main function of a cap is to provide a seal between the chamber and the printhead. Previous products have chosen to seal the cap against the nozzle plate at the plate surface. One disadvantage of this method is that the cap alignment to the printhead must be near perfect (nominal clearances of less than 1 mm as shown in Fig. 6a) because if the lips of the cap seal against one of the nozzles, capillary action will draw ink from within the reservoir inside the print cartridge. The result is a messy service station and an unhappy customer.

Early in the development of the DeskJet 1200C the print cartridge and product engineers decided that the best surface for a cap seal is well outside the nozzle plate. In the DeskJet 1200C the nominal clearance is closer to 3 mm as shown in Fig. 6b.

Wiper. The wiper removes external debris from the nozzle plate without scratching the thin gold protective layer. Any particle in or around the nozzle will misdirect the ink droplet or completely block it from ejecting. In a perfect world the nozzle plate would always be sparkling clean. Thermal inkjet inks are designed to dry quickly and permanently, so if wet ink is allowed to dry on the nozzle plate it becomes very difficult to redissolve and wipe away. Wipers have not changed much from their initial development.

The DeskJet 1200C uses a standard-geometry wiper that looks much like an automobile windshield wiper. Design considerations include material geometry, angle of attack, abrasion and wear resistance, ink compatibility, manufacturability, ease of assembly, user replaceability, and performance over life.

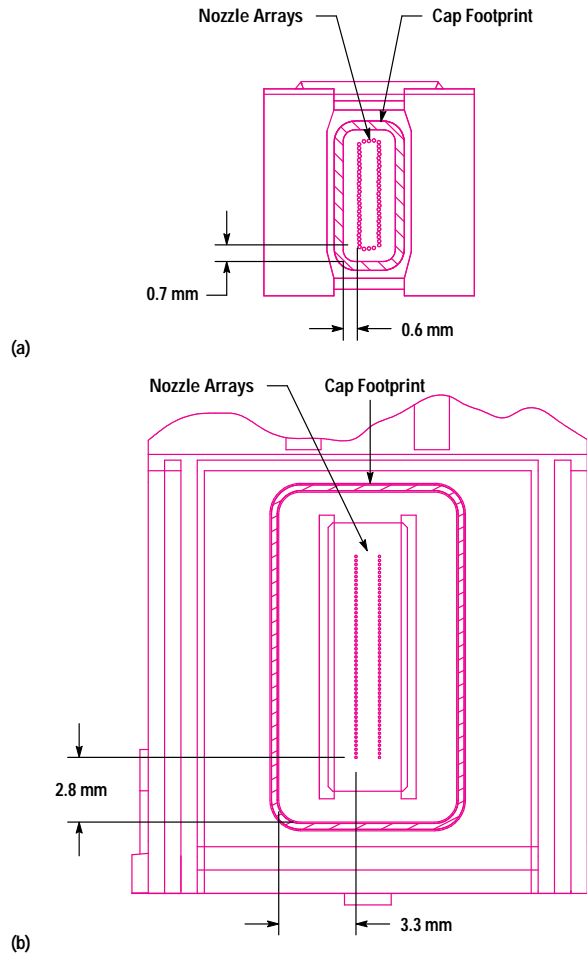


Fig. 6. Nominal clearances between cartridge cap seal and nearest nozzle. (a) DeskJet print cartridge. (b) DeskJet 1200C print cartridge.

Mechanism. Because the DeskJet 1200C is a low-cost, high-volume product, the service station mechanism is designed with a very low part count. Excluding the caps and wipers, the preventive maintenance mechanism consists of only five parts while the priming mechanism consists of 18 individual parts.

The sled assembly is activated in the X direction by print cartridge carriage motion and in the Z direction by four cam surfaces. The capping and wiping forces are a result of two identical wireform springs attached at one end to the structural chassis and at the other to the sled assembly. The cam surfaces are designed to wipe the print cartridge only as the carriage exits the service station on the way to printing. Fig. 7 shows the sled assembly in three different positions.

Maintenance. During certain times it is necessary to spit ink from each nozzle into a reservoir. This purges ink from the nozzle region after extended capped storage, after wiping or priming, and within certain plots. Directly to one side of the service station is a spittoon for this purpose. The spittoon is designed as a bottomless pit with a large-surface-area absorbent to contain as much as four full print cartridge volumes.

Priming. Priming is the drawing of large volumes of fresh ink through clogged nozzle orifices. This action will clear crusted ink both internal and external to the nozzle plate, and will purge small trapped air bubbles. In keeping with the theme of low cost and low risk, the DeskJet 1200C priming system mechanism was leveraged from the PaintJet XL300

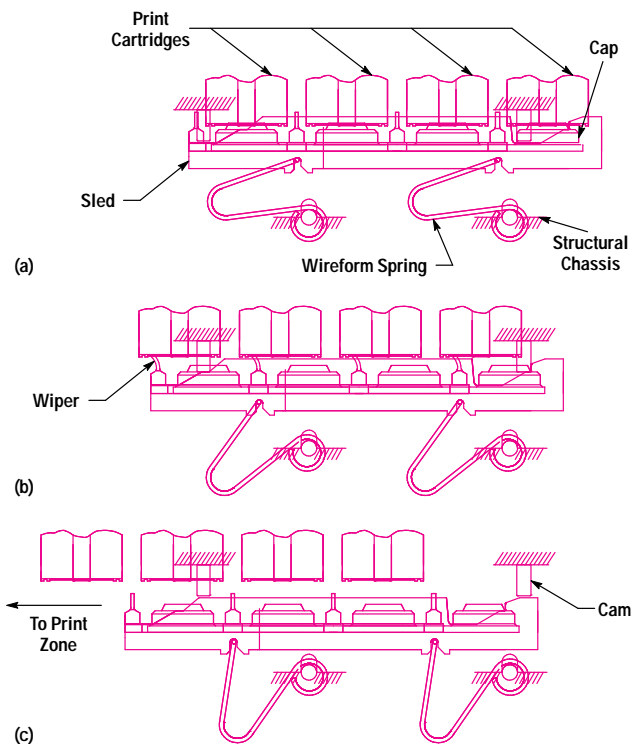


Fig. 7. Three positions of the sled assembly. (a) Print cartridges capped. (b) Wiping print cartridges. (c) Print cartridges clear of caps and wipers, ready to print.

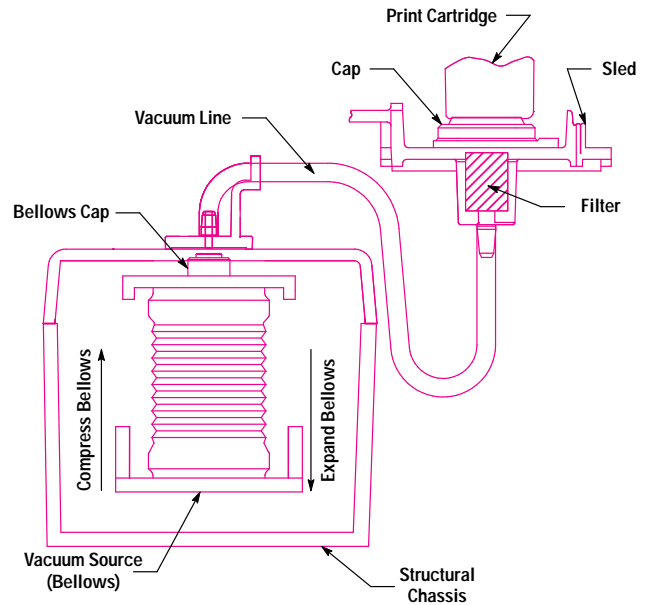


Fig. 8. To prime the print cartridge, the user compresses the bellows using the plunger. The bellows cap seals to the vacuum line and the bellows expands and draws ink from the print cartridge nozzles.

printer (see Fig. 8). To improve on the usability of the system the priming source is routed via four tubes to the service station sled. The user selects which print cartridge is to be primed by positioning a lever directly in front of the print cartridge. The user then actuates the vacuum source by depressing a plunger with a vertical stroke. Audible feedback from the mechanism signals to the user that a corrective action has taken place.

The primer tubes have a tendency to clog with dried ink over the product's life. To address this issue the ink is kept from entering a tube by a filter between the print cartridge and the tube. During a prime the majority of ink removed from the print cartridge remains on the nozzle plate and is cleaned off by the wiper. Any ink drawn down away from the print cartridge is trapped in the filter and does not enter the tube.

Acknowledgments

The authors would like to acknowledge Bill Osborne for his early development work on the service station and Heinz Waschhauser for his refinement and completion of the design. Ron Askeland, Michele Shepard, Frank Drogo, Jason Arbeiter, and Dennis Desouza provided countless hours of support to the service station testing program. For his efforts on the implementation of the service station algorithms, Bill Hilliard deserves special mention. Wistar Rhoads' great contributions to the carriage architecture made the printer design both compact and low-cost. The tooling expertise of Walt Borra, Walt Auyer, and Warren Werkmeister made the very aggressive development schedule possible. Dennis Culver, Richard Berkold, and the entire model shop staff organized and delivered parts on time for all the prototype builds.

Media Path for a Small, Low-Cost, Color Thermal Inkjet Printer

The DeskJet 1200C media path is heated for media independence, requiring development of a new grit drive roller and pinch wheel combination. A new stepper motor was developed to attain the target speed and accuracy. Media flatteners and precise gearing with an antibacklash device contribute to accuracy.

by **Damon W. Broder, David C. Burney, Shelley I. Moore, and Stephen B. Witte**

The media path is the part of a printer that moves media past the print cartridges, stopping and accurately locating the media for printing. The media path also constrains the media in a plane a fixed distance from the print cartridges. A media path should advance media accurately and quickly, be quiet, be inexpensive, hold the media flat, and keep the media the correct distance from the print cartridges.

Fig. 1 shows an overview of the media path of the HP DeskJet 1200C printer. Media stacked in the input tray (1) is individually picked by a media pick roller (not shown) and driven around the curved preheat zone (2) where it is preconditioned (moisture is driven off and the temperature is raised). When the page reaches the pinch/drive rollers (3), the main drive system (4) takes over from the pick roller drive (not shown). Once in the print zone (5) the media is heated further and ink is sprayed onto the page. The heating, soaking, and drying causes the media to move out of its

plane, but the media control shims (6) help hold it flat for better print quality. The page is then incrementally advanced and printed upon until the entire page has been printed. Finally, the page is fed out into the output tray (7) and the process is ready to repeat.

Design Approach

For the office printer market, the DeskJet 1200C is designed to support a wide variety of plain papers, to be HP LaserJet printer compatible, to print text very quickly, to print high-quality graphics, and to be cost competitive. These characteristics forced the design team to face the following challenges:

- Constrain plain papers flat even though plain paper tends to cockle and curl in various directions when ink is sprayed on and heated.
- Print to 50-dot row margins for LaserJet compatibility, even though such small margins allow very little control over media flatness.

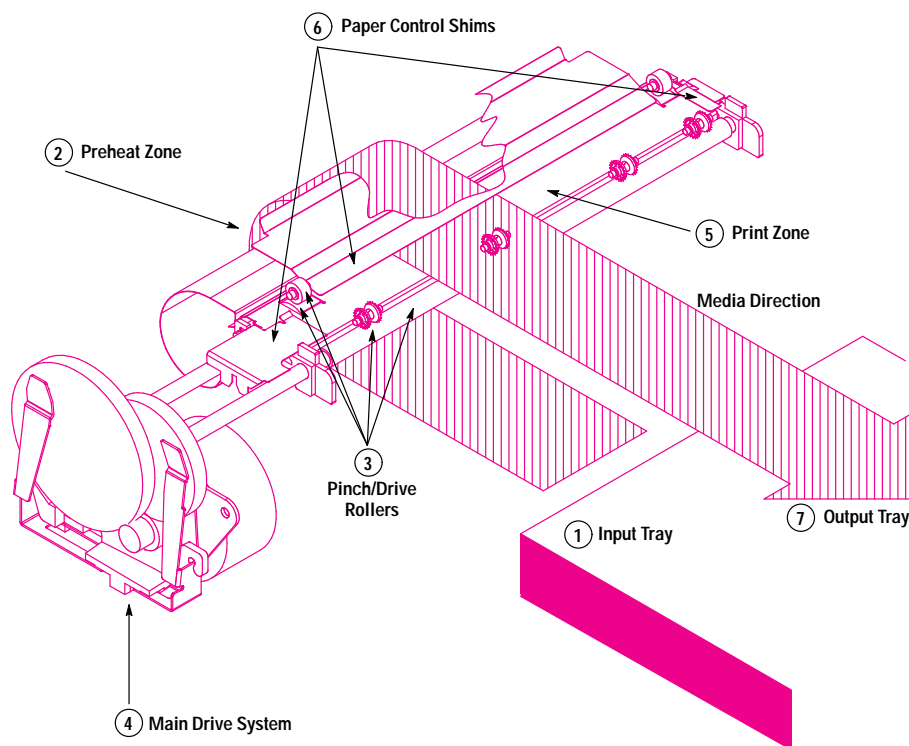


Fig. 1. Overview of the media path of the HP DeskJet 1200C printer. Media stacked in the input tray (1) is individually picked by a media pick roller (not shown) and driven around the curved preheat zone (2) where it is preconditioned (moisture is driven off and the temperature is raised). When the page reaches the pinch/drive rollers (3), the main drive system (4) takes over from the pick roller drive (not shown). Once in the print zone (5) the media is heated further and ink is sprayed onto the page. The heating, soaking, and drying causes the media to move out of its plane, but the media control shims (6) help hold it flat for better print quality. The page is then incrementally advanced and printed upon until the entire page has been printed. Finally, the page is fed out into the output tray (7) and the process is ready to repeat.

- Move media very quickly through the print area while maintaining high placement accuracy for good graphics print quality.
- Keep the price low.

The parts of the media path (Fig. 1) that drive and meter the media include the stepper motor, the drive pinions, the drive gears, the antibacklash device, the shaft bushings, the adjustable plate, the drive rollers, and the pinch rollers. While driving the media these components work together to ensure fast, accurate movement of the print media, which in turn provides the best possible throughput.

The stepper motor provides the fastest response available in an inexpensive motor. Although stepper motors aren't always the most accurate type of motor, the accuracy of the system can be optimized by designing the system so that the motor always moves in multiples of four half steps. Moves of four half steps cancel out all of the error caused by manufacturing variation except the locations of the stator teeth which are formed out of the sheet-metal case of the motor. Used in this way, the stepper motor can provide very fast and accurate moves and is well-suited for driving the media in an inkjet printer.

The gearing system in the DeskJet 1200C is designed to optimize the accuracy of the media drive. A single-reduction drive is used because there are fewer components in the gear train, so this type of drive is more accurate. However, accuracy is not the only reason to use a single reduction. The size and spacing of the drive rollers relative to the print cartridges and heater also pushed the design towards a single-reduction gear train. The DeskJet 1200C relies on a heated media path to dry the ink as it is being printed. To make room for the heater while maintaining control of the print media, the drive rollers had to be much smaller than other inkjet printers had typically used. By using smaller drive rollers, we were able to use a single-reduction gear train.

The spacing of the drive rollers was a critical issue in the design of the DeskJet 1200C. The spacing is constrained by the size of the print cartridges and heater. Thus, we had to trade off room for the heater and print cartridges against control over the leading edge (the star wheels hold the media down against the output drive roller) and print quality in the bottom margins (the main drive roller is more accurate than the output drive roller). As the space between the rollers increases, there is a longer span of media at the top of the page to control with the star wheels and a longer space at the page bottom where the media is driven by the output roller.

A major problem in reducing the shaft spacing was reducing the size of the drive roller. Drive rollers in inkjet printers have typically been rather large elastomer-coated shafts, 40 to 70 mm in diameter. To shrink the roller to a size we could use (< 20 mm) we had to find a different process, one that was new to inkjet printing. We decided to try the grit drive system used in several HP plotters, which consists of a grit-coated metal drive wheel and an elastomer pinch wheel. By using a grit system, we could minimize manufacturing errors associated with the size and shape of elastomer rollers and reduce the size to one we could use. Of course, we then faced many problems adapting the grit drive system to a heated media path system.

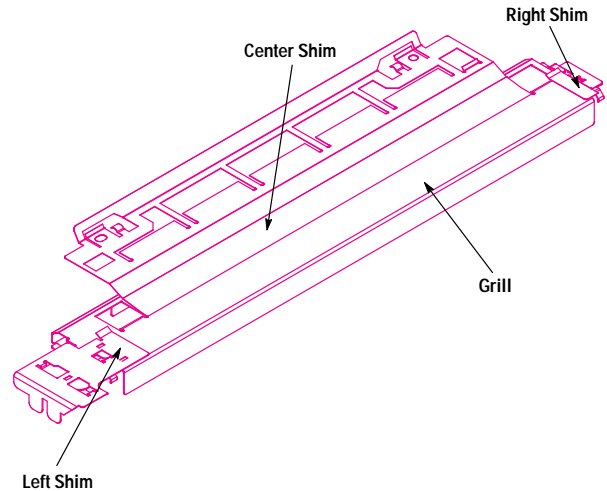


Fig. 2. A grill and three shims hold the media flat in the print zone.

The media path must also hold the print media flat. The environment in the print region is somewhat hostile to paper. The ink soaks the paper, and the heater boils the water out of the paper and dries it out. The DeskJet 1200C is intended to print on any office paper with nearly equal print quality. The heater and the ink design help achieve media independence, but at the same time, the heater and ink wreak havoc with the fibers that make up the paper. The fibers, predominantly cellulose, swell with ink and the paper expands. Then, as the paper is heated and dried, the fibers shrink and the media contracts. None of the expansion and contraction is uniform from one side of the media to the other, so the media tends to move out-of-plane. To print with high quality, the distance from the print nozzles to the print media must be accurately maintained. We hold the media flat against a grill (which covers the heater) with three shims—center, left, and right, as shown in Fig. 2. The fixed right shim constrains the right edge of the media and acts as the zero reference point for printing. The adjustable left shim adjusts to A and A4 sizes while constraining the left edge of the media. The center shim helps keep the media flat against the grill and helps keep the media from crashing into the print cartridge. The center shim also allows printing very near the bottom edge of the media—as close as 5 mm.

As the paper advances out of the print region, we also hold it down with the star wheels. These systems provide good control over the media, keeping it constrained in a plane at a fixed distance from the print nozzles.

Heated Media Path

The DeskJet 1200C was envisioned to support a broad range of media: not just A and A4 sizes, but also glossy paper, transparency film, and virtually any paper on the market (at one point we were even printing on paper bags). With such a wide range of media as the goal, and the added challenge of fast throughput, it became evident that the DeskJet 1200C would need a heated media path to meet these goals with any kind of reasonable print quality.

The heated media path of the DeskJet 1200C (see Fig. 3) is composed of two main components: the preheater and the main heater. The preheater is a flexible polyimide heater that serves as the inner guide for the media. As the media is

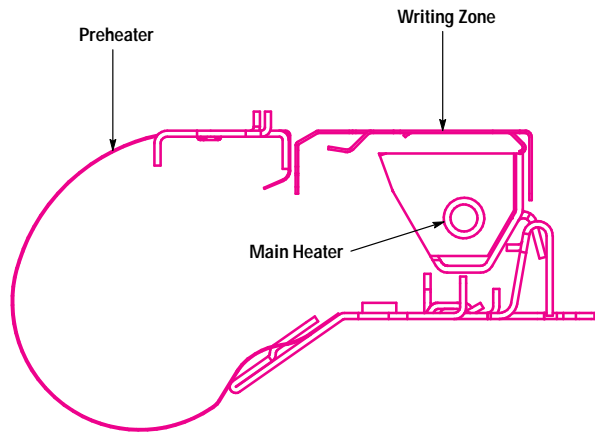


Fig. 3. Heated media path.

fed up into the main heater and the writing zone, it is wrapped around the preheater. This contact allows the preheater to precondition the media so that when the media reaches the writing zone it is much more dimensionally stable. Much of the paper fiber shrinkage that occurs with heating happens before the paper reaches the writing zone.

The main heater consists of a Kanthal wire and a quartz tube. Current drawn through the wire causes it to heat up and emit infrared radiation. The radiation and convective heat from the bulb help evaporate the water from the ink in the writing zone. This increase in the evaporation rate of the ink allows increased throughput and improved print quality over a much broader range of media.

Drive Roller Development

The DeskJet 1200C media advance is controlled by a high-pressure nip concept (drive roller and pinch wheel) located near the left and right media margins (Fig. 4). As mentioned earlier, this gives a clear advantage in space conservation and design simplicity over other inkjet products using large-diameter drive rollers and low-pressure nip concepts.

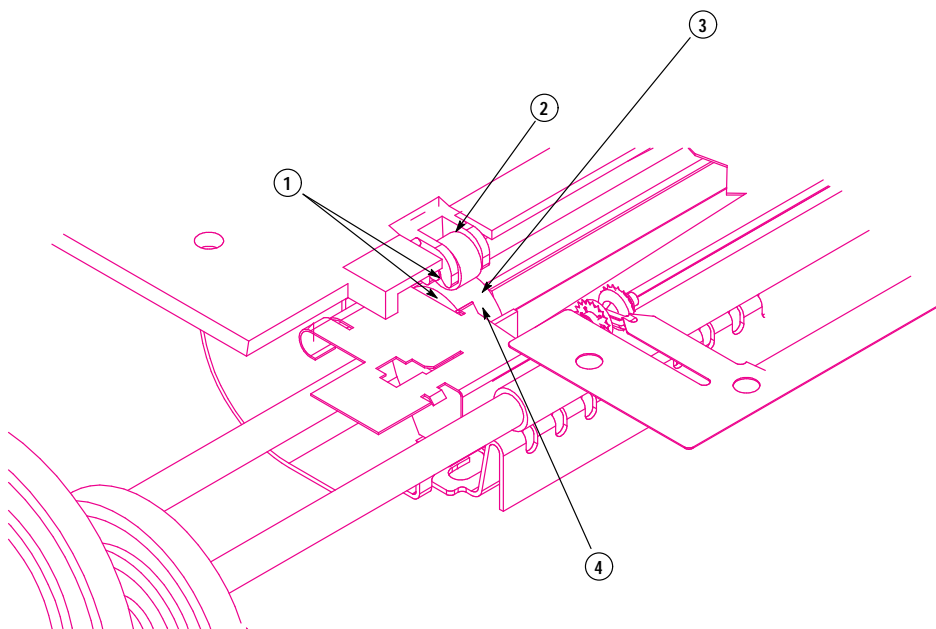


Fig. 4. Drive roller and pinch wheel. (1) Nip area (drive roller and pinch wheel), one of two in the printer. (2) Pinch wheel. The pinch wheel rolls on the media above the drive roller to apply normal loading of the media into the traction surface of the drive roller. (3) Drive roller. Rotary motion of the drive train is converted to linear media motion. The surface must not slip or leave tracks in the media. (4) Pitch diameter is twice the radius from the drive axle center of rotation to the contact zone between the media and the traction surfaces.

A traction surface designed to tolerate thermal shock with a low thermal expansion needed to be developed. The low-cost, high-quality advance mechanism goals also required a reliable manufacturing process that would produce 100% in-specification parts.

The traction surface characteristics were initially defined from a customer satisfaction viewpoint:

- The combination of nip pressure and drive roller roughness could not mar transparencies or leave tracks in plain paper.
- The traction surface had to push the media with no slippage.
- Banding had to be controlled much more tightly than before to meet print quality expectations. This meant that the traction surface had to advance the media consistently a constant distance for a given arc of rotation, that is, the pitch diameter had to be as tightly controlled as technology would permit. The printer's performance could not be adjusted to compensate for poor control of this specification in manufacturing. Print quality swath banding has a 1:1 correlation with this assembly.
- The cost had to be low and the process compatible with high-volume manufacturing.
- The materials selected had to survive with no degradation of their properties within the thermal operating environment of the printer.

A fundamental design goal for the Deskjet 1200C drive roller assembly was to develop a roller surface that would not slip on any media type. This was approached from a mechanical friction and traction point of view. Lab tooling adequate to characterize the traction surface had to be developed quickly. The reality of our schedule required high-risk decisions with data lagging by several months.

Concurrent development was started for lab tools, prototypes, and metrics simultaneously. We had to allow the development of the drive roller assembly to slip out of phase with the rest of the project and get convergence by the time of the production build.

Stepper Motor Simulation Model

The model used to simulate a permanent magnet stepper motor for the simulations described in the accompanying article originated from a classic control systems point of view. The model includes simple position and velocity feedback control algorithms. Fig. 1 is a block diagram of the model.

A nonlinear block in the model allows the nonlinear characteristics of the stepper to be included. This block makes the stepper torque output match the desired torque for a given error signal.

The resultant nonlinear system was linearized by running it at a very high sample rate of 40,000 samples per second. At this sample rate, speeds, positions and currents are changing very slowly. Hence linear control systems analysis is valid.

The model was used to compute velocity profiles with several different motor resistances, inductances, and so on. The lowest-resistance motor available in a permanent magnet motor at this time was an 8-ohm motor. Fig. 2* shows that the

simulated velocity clearly does not reach the desired 1400 steps per second. This motor fails and stalls in the real system. In Fig. 3,* the simulated velocity of a 2-ohm motor is shown. In this successful run, it appears that the motor has no trouble reaching the desired 1400 steps per second. This motor was built and is now the motor being used in the DeskJet 1200C printer.

The currents in a failing stepper motor are shown in Fig. 4* and the currents in a stable, running stepper motor are shown in Fig. 5.* In the failing stepper motor, the currents do not even reach their normal operating levels before they are switched again. The characteristic hook in the graph of these currents reflects reality very well for the case of insufficient voltage used to drive the motor.

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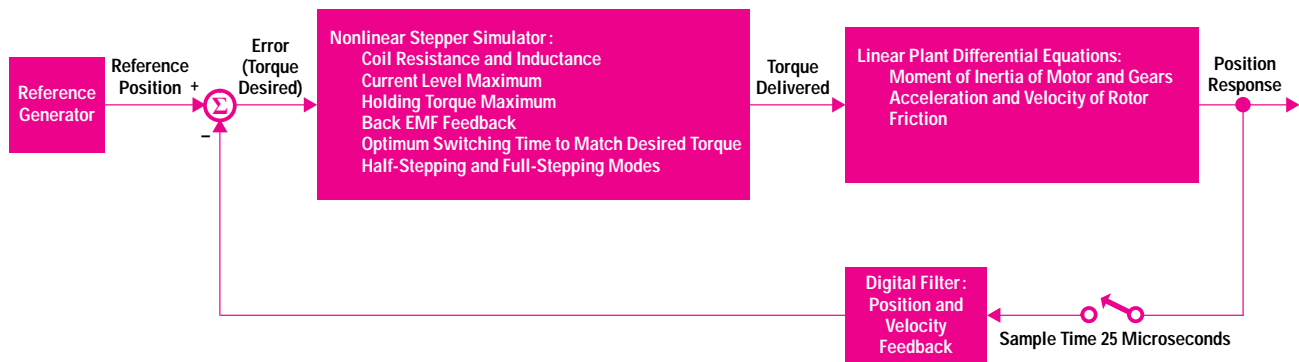


Fig. 1. Block diagram of the theoretical stepper motor model.

* See top of next page for Figs. 2, 3, 4, and 5.

The term traction was used to define media slippage with the drive surface to avoid preconceptions of friction behavior. (Paper has a composite surface of fibers and fillers that cause its frictional characteristics to be nonlinear with normal forces beyond a relatively low surface shear stress.)

The characterization efforts revealed interactions with printer components not previously considered. Affected components were redesigned and the traction surface successfully developed in concert with these components. Analytical tools to measure system and component performance were developed or enhanced by this project. This greatly improved correlation of print quality goals with measured performance and design specifications.

High-volume processes at multiple suppliers for this assembly were characterized with proven process margins. Supplier inspection processes were improved to fit part requirements and inspection metrics.

Media Motor and Antbacklash Device

The goal for selecting the Deskjet 1200C media axis drive was to design a motor and gearing system that is simple and compact and has better speed and accuracy than we had

ever achieved before. Not only did this new gear drive system have to have improved performance, but it also had to be less expensive.

One key element of the media drive system is the motor selection. The HP PaintJet, PaintJet XL, and PaintJet XL 300 printers use a hybrid stepper motor to drive gear trains that control two roller media drive systems. These systems have relatively high inertia and are limited in speed. They also have multiple idler gears for the purpose of transferring position control to a different location in the machine. For the HP DeskJet 1200C printer, a decision was made to use a double-pinion approach to eliminate the idler gears.

For low cost, we believed that a permanent magnet stepper combined with an antbacklash device would be as accurate as the hybrid stepper system. The key issues were: How do we design a low-cost anti-backlash device? and, How do we get the speed and torque that we need out of this low-cost stepper motor?

To determine whether the permanent magnet stepper would work, a theoretical model was developed that allows the simulation of the motion of a stepper motor from a standing

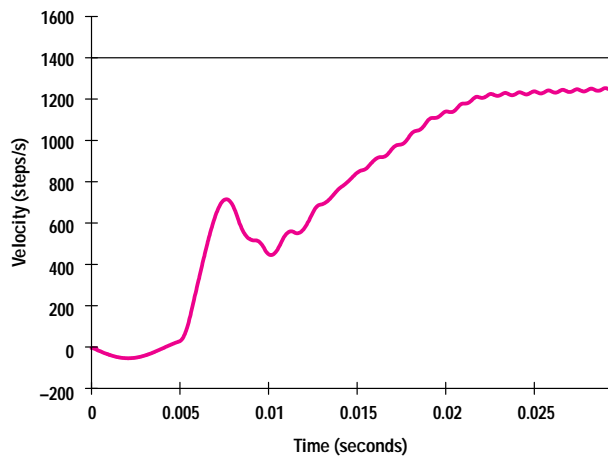


Fig. 2. Simulated velocity profile of a failing motor (8-ohm).

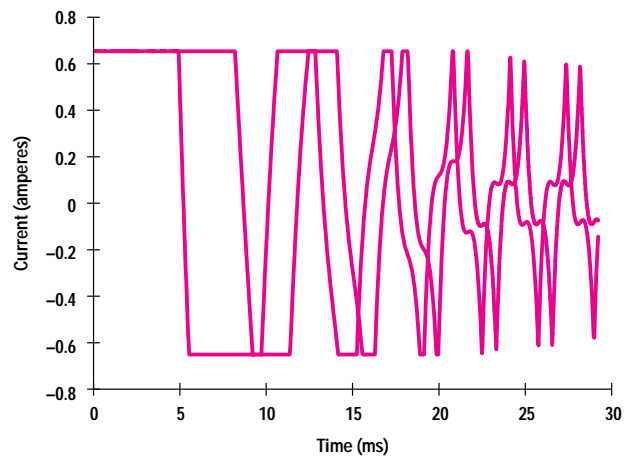


Fig. 4. Simulated currents in a failing motor.

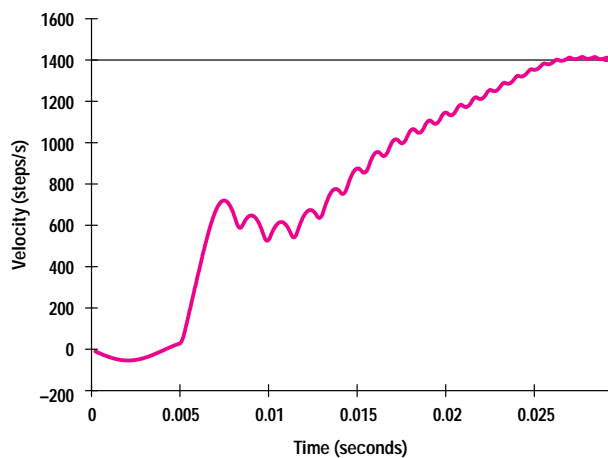


Fig. 3. Simulated velocity profile of a good (2-ohm) motor.

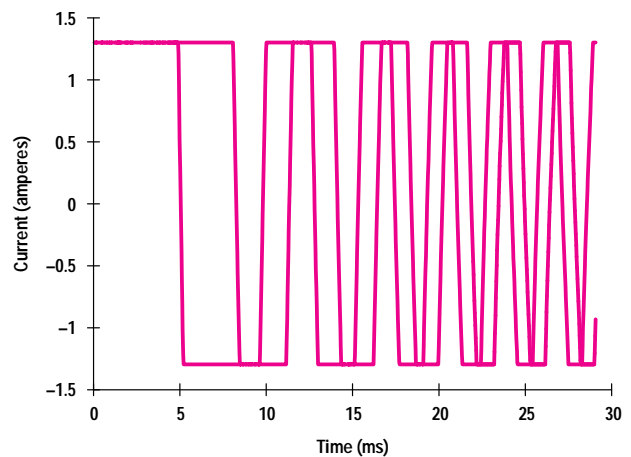


Fig. 5. Simulated currents in a stable, running stepper motor.

start through high speed and back down to a stop (see “Stepper Motor Simulation Model” on page 75). This model includes the motor, system inertia, inductance, motor resistance, and friction. It also dynamically calculates back-EMFs and motor currents.

This simulation predicted that a motor with a resistance of one or two ohms could run significantly faster than previous DeskJet motors. Speeds of 2000 full steps per second (2500 r/min) were predicted as possible high-end speeds where older permanent magnet motors had not been run much faster than 600 to 1000 steps per second.

A motor vendor was located that would be willing to wind the motor coils with a heavy-gauge wire and prototype motors were assembled. These motors performed at the predicted speeds and astounded the motor R&D engineers themselves! They previously had not built permanent magnet steppers with this kind of speed capability. This vendor developed manufacturing processes to produce these low-resistance coils in production and ultimately won the contract to provide HP with these motors for the Deskjet 1200C printer.

Fig. 5 shows the complete motor, gears, and backlash system.

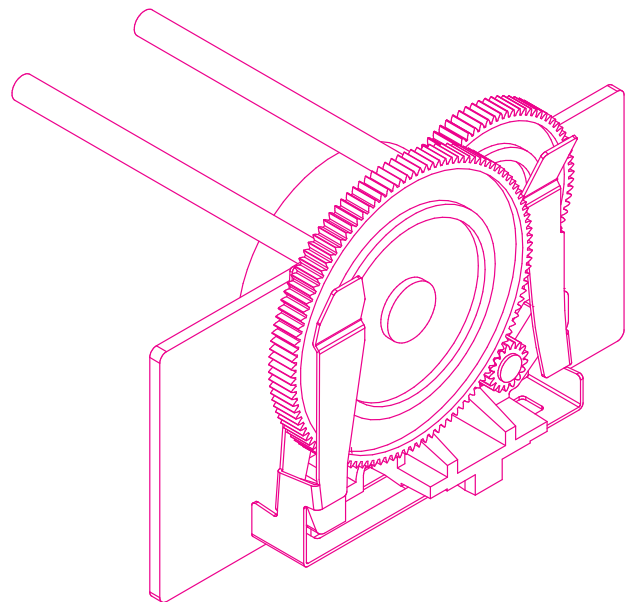


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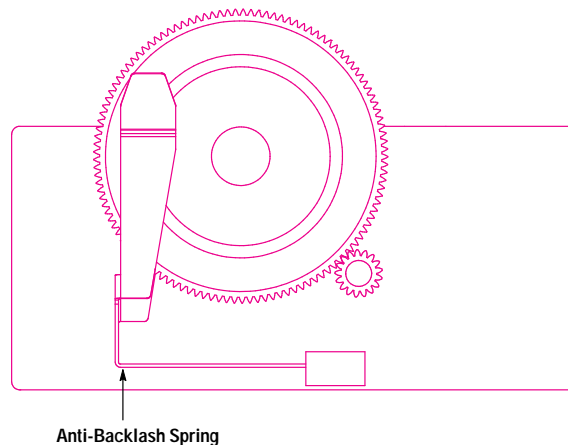
Reducing Stepper Noise. Once we had the speed that we needed, we had several more hurdles to pass. It was necessary to control the motor and make it start and stop precisely without the noises that normally come from stepper motors. When the first DeskJet 1200C lab prototypes were built, people were very concerned about the stepper noise. Hardware was developed that allows the dynamic response of both the motor and the gear-driven shaft to be measured. This hardware was combined with personal-computer-based software that makes the process of smoothing out the step profile of the motor relatively easy. Because the designers had been clever enough to make it easy to download step times to the printer, it was possible to try out different combinations of step times quickly and observe the response of the motor and drive shaft visually (in addition to hearing it). The dynamic response was successfully smoothed out and the system became much quieter. At the same time, we were also anticipating problems with overshoot.

Controlling Backlash. Fig. 6 shows the function of the anti-backlash device. The purpose of this sheet-metal spring is to keep the teeth of the gears meshed tightly even if the motor backs up slightly. If the gears were to become unmeshed, the resultant accuracy error would be twice as much as all other error sources combined.

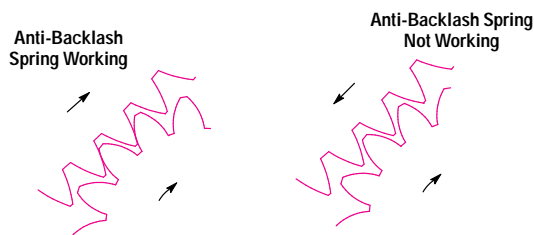
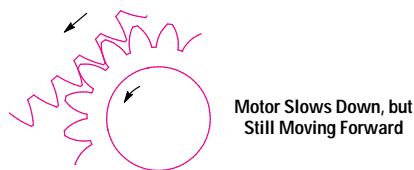
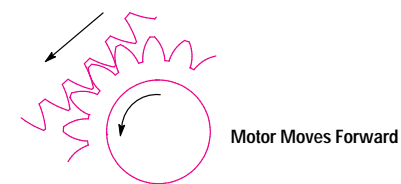
The DeskJet 1200C media axis completes a 1/3-inch swath advance in under 58 milliseconds. (For comparison, the PaintJet XL300 completes a 1/6-inch swath advance in about 200 milliseconds.) Hence, it was expected that it would be difficult or impossible to prevent gear backlash. However, we came up with a way to reduce this backlash. The idea is to use a piece of sheet-metal steel that pinches the gears, adding friction so that when the motor stops and backs up, the gears follow it backwards. This steel antibacklash device has three springs built into one component. The first spring applies a controlled pinch force on the gear. The second spring is stretched forward every time the motor moves forward and provides the restoring force or antibacklash function. The third spring provides a thrust load that keeps the plastic gears pushed against the motor mounting plate.

Motor Pinions. One of the most difficult challenges on the HP DeskJet 1200C printer was to achieve an overall accuracy goal that was as good as the PaintJet XL300 over twice the distance of that printer. It turns out that one of the key components in the DeskJet 1200C mechanism is the quality of the motor pinions. We chose to hob the pinions instead of molding them because their relatively small size makes hobbing relatively low in cost. Also, hobbing is substantially more accurate. Gear accuracy is commonly measured in the industry, and the key measurement is called total composite error or TCE. This measurement is very similar to runout and essentially behaves the same way as runout. However, while it is easy to measure runout on a motor-driven smooth shaft, it is difficult to measure the TCE of a pinion after it has been mounted on the motor shaft, especially with a stepper motor. To measure the TCE of a pinion after it has been mounted on the motor shaft, it is necessary to turn the motor very smoothly and slowly at only a few r/min. So, first we designed the stepper motor (which is by nature very oscillatory) to go extremely fast, and then we tried to drive it at very slow speeds. We were only able to make the motor

move at slow speeds by using two function generators constrained in a phase-locked loop to be 90 degrees out of phase, then connecting their amplified outputs to the phases of the motor. Effectively, this became a sine-wave drive for the stepper, and it did successfully drive the permanent magnet



The Function of the Anti-Backlash Spring



Motor backs up slightly and stops. Teeth stay tightly meshed because the backlash device pulls the big gear backwards against the small gear.

Motor backs up slightly and stops. Teeth have become unmeshed because the big gear continued to move forward while the motor was backing up. This is a failure.

Fig. 6. Controlling the backlash. The large drawing at the top shows the function of the antibacklash device. The purpose of the backlash sheet-metal spring is to keep the teeth of the gears meshed tightly even if the motor backs up slightly. If the gears were to become unmeshed, the resultant accuracy error would be twice as much as all other error sources combined. The middle drawings show the motor moving forward and the motor slowing down but still moving forward. The two drawings on the bottom show the backlash spring working (left) and the backlash spring not working (right).

stepper at slow speeds. For the first time we could measure pinion quality after the gears had been mounted on the motor shaft. With this measurement ability, we were able to work with the vendor and resolve tricky problems such as damaging the pinions and bending the motor shafts while mounting the gears on the shafts. The resultant print quality of the HP DeskJet 1200C printer is good enough that few swath advance accuracy problems have occurred in production.

Media Drive Accuracy

The media advance accuracy is an important metric of the performance of the media drive system. As media moves through the printing region it is stopped, printed on, and then advanced to the next printing location. The distance it moves each time depends upon the print mode and what is being printed. Print quality for both text and graphics depends on advance accuracy. However, graphics print quality is more dependent on advance accuracy because there is no blank space in which to hide the advance error. Every advance made during graphics printing has the potential to show a print quality error, whereas during text printing it is possible to avoid splitting text between advances and thereby avoid showing advance error.

In the early stages of development the design team needed an estimate of the drive accuracy of the printer. A mathematical model was constructed that simulates an advance made by the worst-case components in the worst possible orientation. This model provided a good guide to what sort of tolerances we needed in our manufacturing processes, but was too conservative to simulate what we expected most advances to look like. The next model built was a Monte Carlo model that chooses components from simulated distributions and orients the parts randomly, much like a manufacturing process. When this model is run for a large number of cases, a good approximation of the expected mean and standard deviation of an advance is produced. Once the mean and standard deviation are known, process control of advances is possible. The goal of the modeling effort was to simulate advances and establish tolerance limits on advance accuracy. This goal was achieved and the process limits were confirmed by measuring drive components, building machines, and measuring their swath advances.

The DeskJet 1200C project was able to use tools previously developed for media advance measurement for other printers. The best tool we found is an optical vision system which, when given a specific plot, measures a series of advances and reports the data. For our purposes, predominantly graphics print quality, measuring 32 nozzle advances provides all the information we need about the drive system. The 32-nozzle advance data can easily be extrapolated to the other advance distances we are interested in.

Fig. 7 shows media advance measurements down the length of a page. This data was processed to find the mean and

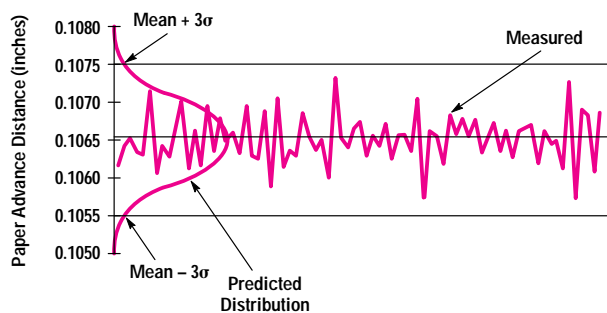


Fig. 7. The measured media advance down the length of one page of a single machine is shown along with the predicted accuracy calculated with measurements of the drive components as inputs to the model, which is shown as a distribution. The actual output of the model is the mean and standard deviation for a given machine.

standard deviation, which were compared with the model. First, components were measured and used to build a set of machines. Then the swath advance of the machines built with these components was measured. Finally, the statistics of the measured swath advance were compared with the results from the model with the measured components as inputs. Fig. 7 also shows the results of the simulation: the distribution of swath advances predicted by the model. As can be seen, the measured advance fits within the predicted distribution and the mean and standard deviation of the predicted distribution agree well with the measured mean and standard deviation. Thus, we confirmed the accuracy of our fabrication processes, the simulation model, and the printers we manufacture.

Acknowledgments

As with any large development effort, there are innumerable people without whose contributions this product would not exist or function as smoothly as it does. We would like to thank Gerold Firl, Mike Green, Joe Milkovits, Tim Zantow, and Tom Halpenny for their contributions to the media path. We would like to thank Ron Kaplan for his valuable assistance in the early characterization and tooling development, Frank Nasworthy for his expertise in designing the pinch wheel, Steve Witte for his assistance with the hardware connectivity and programming skills, Damon Broder for his overall support of the paper advance system, Jeff Wilson and Dennis Culver for their design and fabricating assistance in tooling design, and our staff of lab technicians—Tau Ngo, Nhuong Nguyen, Robert Schmidt, Damon Johnson, and Danny Zepeda—for their many long hours of testing. Thanks also to Steve Gaddi for his support of paper advance testing.

HP-UX is based on and is compatible with UNIX System Laboratories' UNIX* operating system. It also complies with X/Open's* XPG3, POSIX 1003.1 and SVID2 interface specifications.

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Automated Assembly and Testing of HP DeskJet 1200C Print Cartridges

The assembly system is flexible and modular. A performance monitor collects data for quality control. A standardized print engine is used in several applications.

by William S. Colburn, Randell A. Agadoni, Michael M. Johnson, Edward Wiesmeier, III, and Glen Oldenburg

As volume requirements for print cartridges increase beyond the capability of laboratory tooling, the need for an automated assembly system becomes apparent. The automated assembly system for the DeskJet 1200C print cartridge is designed to meet a set of objectives that includes autonomy through distributed control, flexibility of assembly process order, and efficiency through commonality of designs and components.

Each process station or small group of process stations has the ability to operate in a stand-alone mode. In this manner, many tools can be debugged and qualified simultaneously without reliance on one large controller. The design of the assembly system allows processes to be added, subtracted, or relocated without significant disruption of the line.

The assembly system is designed around a common set of tooling philosophies and component selections. Designs such as those for print cartridge fixturing mechanisms follow a common concept from tool to tool. In this way, discoveries made on one tool can be easily leveraged to other tools and processes online.

Modules of the assembly system are based around a common tooling platform (see Fig. 1). This approach has helped the team to achieve many of the objectives of the project

early on, including integration of material handling, local process control, and management of electrical, pneumatics, and plant vacuum into a standardized design. As a tooling platform nears completion and is ready for qualification, all facets of tool operation can be verified before the tool is installed in the assembly system. Should the need arise to add or relocate a process, tooling platforms can be easily disconnected and moved. A common facilities interface for each platform ensures that a platform can be moved anywhere on the line with minimal impact on adjacent processes. The inherent flexibility of the assembly system has allowed reconfiguration of the line over a weekend with a seamless production startup on the next working day.

A programmable logic controller (PLC) is responsible for monitoring the status of sensors and switches within a platform, the state of guards and shielding, and operation of the pneumatic cylinders, motors, and other peripheral devices used to perform the assembly processes. Input/output flexibility within the PLC allows the same controller to switch TTL logic levels as well as high-current ac loads. In cases where specialized processing capability is required, such as for machine vision measurement for an inspection process, a dedicated controller is used to perform the function and provide a simple go/no-go response to the PLC. The distributed nature of the control system allows many different types of work to proceed simultaneously. For example, an engineer can be qualifying one part of the line while a technician updates code on an adjacent tool.

Factory Performance Monitor

A factory performance monitor system monitors and reports on factory productivity measures such as yields, efficiency, throughput, up time, down time, cycle time, scrap, and production volume. The overall system employs a distributed, client/server architecture and is composed of several programs running on different platforms (PCs and workstations) communicating over a local area network (LAN).

Each tool's PLC maintains a standard set of data including good parts in and out, run time, wait time, down time, cycle time, machine downs, mean time between failures, mean time to repair, and mean time to respond. The PLCs are networked together along with a PC host machine. A program running on the PC continuously queries the production data table on each tool, performs calculations, formats the data

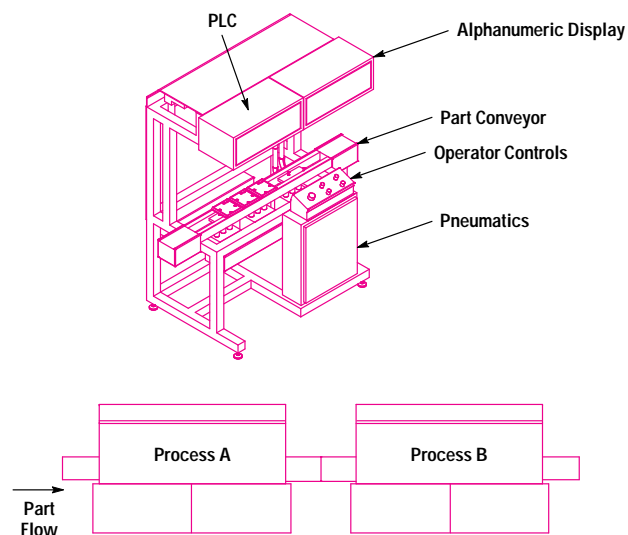


Fig. 1. Assembly system tooling platform and line configuration.

and sends it as a package to a server program running on a separate workstation. The server program receives the data package and makes it available to client programs via the site LAN.

The client program for end users comes in two windows-based flavors: a Microsoft® Windows version for desktop PC users and an OSF/Motif version for workstations or X terminals on the factory floor. After connecting to the server, clients receive data packages and update a graphical view of the factory, using buttons that change color to represent each tool and its current status (running, down, or waiting for parts to process). When a tool button is pressed using a mouse pointer, a window pops up to display a real time summary of that tool's performance. A top-level menu is used to select options such as module or overall line performance, to set alarms, or to review production summaries of previous shifts.

Additional client programs are used to pull periodic summaries of production data for reporting and database archiving. The information from this system has proven to be indispensable in managing the factory, identifying areas for improvement, and planning.

Quality Control

Two primary design goals for the factory affect the strategy for process quality control:

- Emphasize inline, early detection and correction of process quality problems (as opposed to end-of-line audit tests)
- Design for and maintain local control of all process tools, doing as much quality control at the local tool as possible (as opposed to off-tool quality control).

The emphasis is on real-time, local process control and alerting rather than on data archival and off-tool testing. Therefore, process control for a particular tool is first accommodated within the tool. Off-tool statistical quality control is used only where direct process control and real-time alerting do not suffice.

A comprehensive quality control plan was first developed that described the key process performance measures for each process along with the appropriate level or method of quality control to monitor the process performance measures. The quality control methods range from simple go/no-go checks to online, real-time statistical quality control.

System tools were developed to monitor process parameters using industry-standard statistical quality control techniques. The statistical quality control system uses a graphical user interface (OSF/Motif) and is designed to be a generic, project independent tool that is configurable for any statistical quality control test. The statistical quality control system has two operating modes:

- Offline sample test bed. Print cartridge samples are tested offline periodically using various test controllers that communicate with the statistical quality control system over a serial port.
- Real-time statistical quality control. The system monitors the output data files of any process, performing real-time analysis. X terminals are located near the tool, providing immediate feedback to operators about the health of the process.

In both modes, the statistical quality control system's graphical outputs indicate when a process is out of control or if a print cartridge parameter is out of specification, and it is the responsibility of the operators or technicians to take appropriate action. Engineers are responsible for setting control limits, sampling frequencies, and action plans for each statistical quality control test.

Automated Quality Tester

Following final assembly, the quality of each DeskJet 1200C print cartridge is evaluated. All print cartridges are tested by an automated test tool. The tester is based on the original tester design for the DeskJet print cartridge and represents an ongoing evolution in print cartridge tester design.¹⁻³ The objective of the tester is to exercise the print cartridge and measure its attributes with respect to print cartridge specifications. The two tests used to measure print cartridge quality are a machine vision analysis of printed images and the measurement of print cartridge electrical parameters.

The tester can be divided into four functional areas: print mechanism, vision analysis engine, electrical tester, and system controller. The print mechanism moves media beneath the print cartridge while the test pattern is being printed. Tensioning, supply, and takeup are also managed by this mechanism. Once printed, test patterns are analyzed by the vision engine. CCD cameras supply images to the vision engine where they are processed and evaluated. Finally, the electrical tester verifies the print cartridge's electrical integrity. The results from both the vision engine and the electrical tester are sent to the system controller where they are collated and forwarded to the central line controller.

The machine readable print sample (Fig. 2) is composed of two primary patterns. One pattern is used to detect the print mode failures of banding and horizontal trajectory. The other pattern provides a means of analyzing individual nozzles for dot size and vertical trajectory. Dot size provides a rough estimate of a more significant parameter, drop volume. In addition, the fragile nature of the die and TAB beam attachments require electrical testing following print cartridge assembly. The interconnects are probed for open and short circuit conditions and for parametric measurements of special die features.

Print quality results depend heavily on the characteristics of the medium on which the patterns are printed. Print sample positioning within the camera field of view can vary based on the elasticity of the medium, requiring periodic camera adjustment. Moreover, variations in ink bleed along the medium fibers can complicate the issues of vision analysis.

The tester features several advancements beyond previous print cartridge tester designs. Hardware capabilities are extended to provide automated, closed-loop lighting level and color filtration adjustment. Programmable components are included to provide support for both the DeskJet 1200C and DesignJet 650C cartridges. Vision processing algorithms were developed that are insensitive to fluctuations in lighting and magnification levels, and that allow cycle-time improvements through the simple addition of off-the-shelf vision engines. Statistical tools were developed to analyze real-time system performance. With all programmable devices

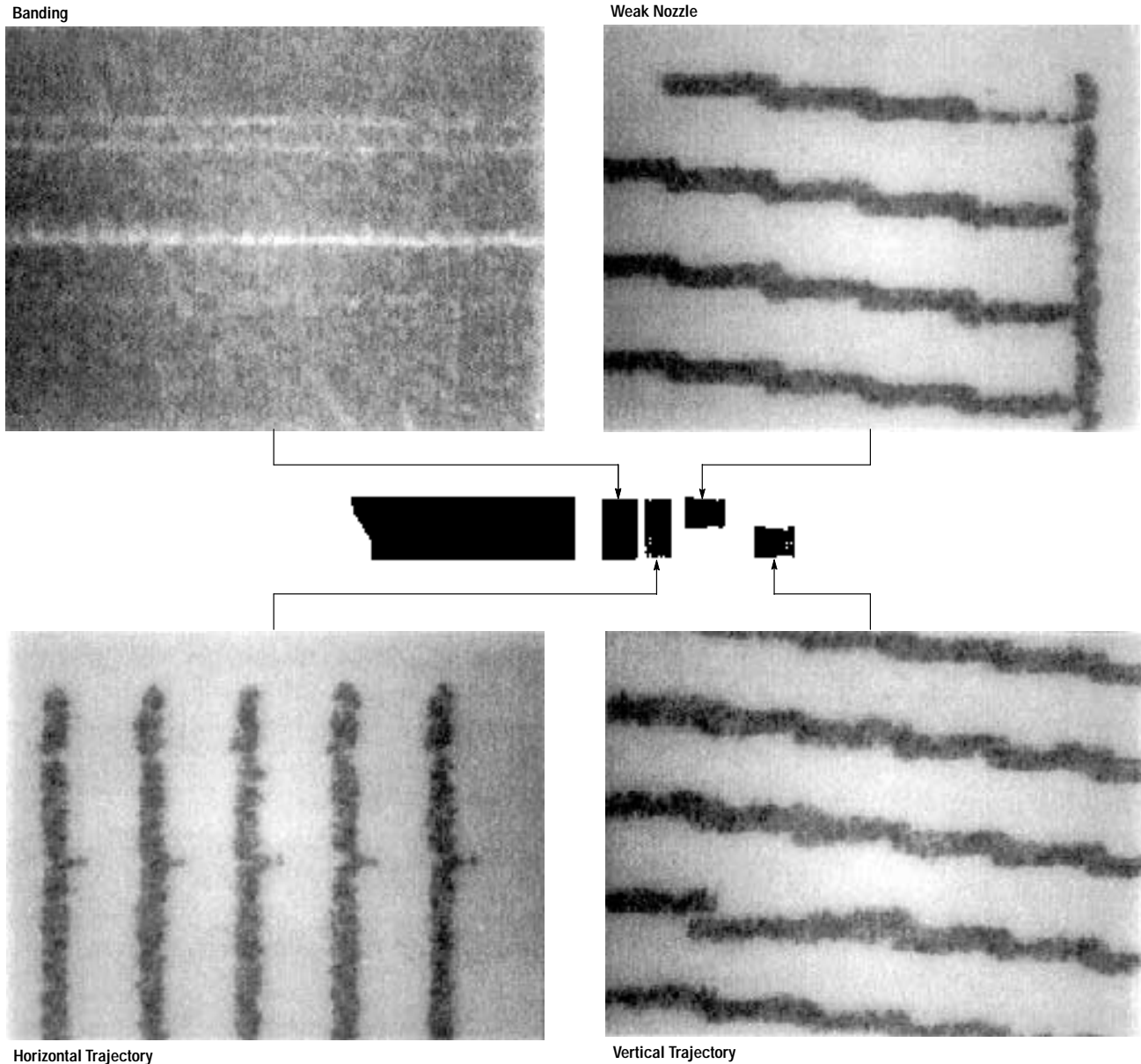


Fig. 2. In the print cartridge quality tester, a machine vision system scans the test pattern (center) printed by each cartridge to detect various defects.

linked through a single workstation, it is possible to change individual components without preconfiguring them.

A Print Engine for Multiple Needs

New print cartridges are different from those for older product lines. Sometimes the differences are substantial. Every print cartridge design must be thoroughly tested well before its companion printer exists. A flexible tester print engine called SPOT+ makes this possible (SPOT+ is not an acronym or abbreviation). In the DeskJet 1200C print cartridge quality tester described above, and in other print cartridge testers, SPOT+ engages the cartridges and fires them. Fig. 3 is a block diagram of SPOT+.

SPOT+ is very different from HP's production model printers because it satisfies a different set of needs. Unlike any production printer, SPOT+ must work with many types of print

cartridges. It must also be independent of printer mechanics. Finally, it must be flexible enough to be used in various kinds of test applications.

SPOT+ uses print cartridge firing orders, print cartridge maps, programmable firing waveforms, and programmable print cartridge drive voltages to gain independence from print cartridge types. The firing order is a data structure that works with special hardware to control which nozzles are fired together and when they are fired relative to other nozzles. The firing order helps designers optimize the physical layout of each print cartridge for fluid dynamics and thermodynamics. The print cartridge map is a data structure that allows the firmware to shuffle print data around to match various wiring configurations. Wiring is influenced by print cartridge layout, flexible cable layout, and the layout of the driver card being used.

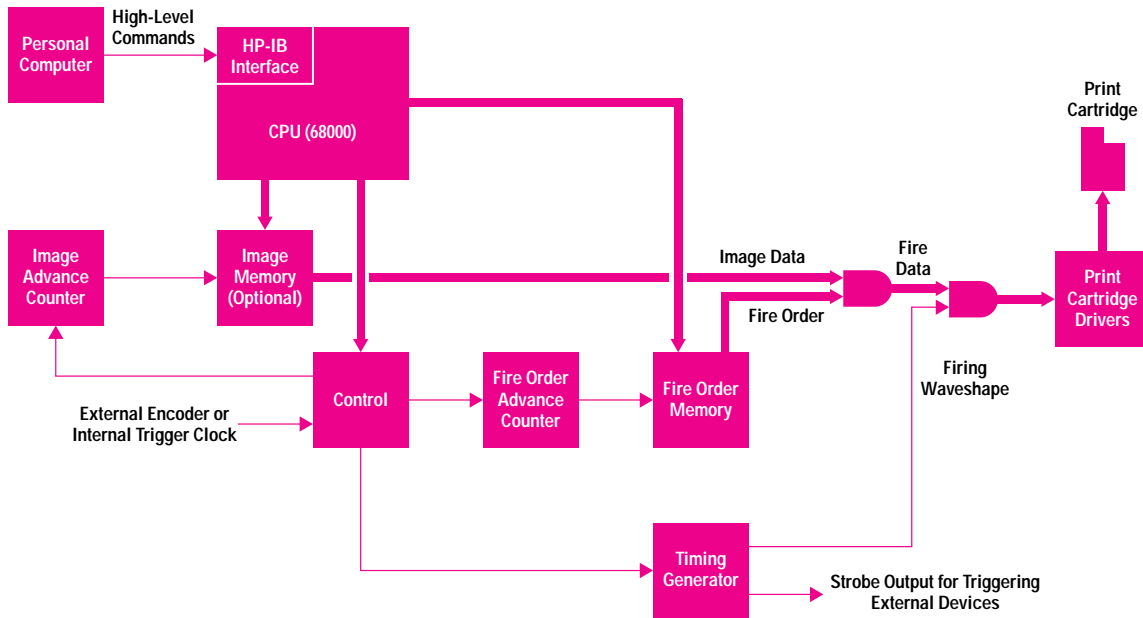


Fig. 3. Block diagram of the SPOT+ print engine.

All testers that use SPOT+ take advantage of the firing orders, print cartridge maps, programmable firing waveforms, and programmable print cartridge drive voltages. Most testers also use SPOT+'s ability to fire bursts. A burst is a firing of a selectable number of drops from one or more nozzles. Nozzles can be turned off by clearing their control bit in a mask data structure. The mask feature is important for the many different types of testers. These testers need to disable nozzles that have problems to prevent them from affecting the tests on the remaining good nozzles.

Two types of testers that do not use burst firing are printer emulators and print quality testers. The printer emulator prints recognizable images much like any printer. Its advantage is that it allows a print cartridge to print images before the print cartridge's companion printer product is designed. The print quality tester is a manufacturing tool that also prints images, as described above.

SPOT+ includes measurement circuitry so that print cartridge parameters can be monitored. Nozzle resistor continuity, nozzle resistor resistance, drive voltage, and operating temperature can all be measured. For example, a resistance scan tester uses the resistance measuring feature to report the nozzle resistance nozzle by nozzle. This information is used to exclude bad nozzles from further testing. Measurements of resistor continuity and drop ejection serve similar purposes. Drop ejection (see below) is detected with additional hardware.

SPOT+ supplies a hardware output called the strobe. It is used in experimental testers to inform other hardware that a particular nozzle has just fired a drop.

In addition to the burst and image modes of firing, SPOT+ also offers an autoburst firing mode. The autoburst repeats a series of high-frequency bursts at a much lower repetition frequency. This permits testers to explore high-frequency

print cartridge firing while allowing the print cartridge sufficient time to recover for the next burst of drops.

The flexibility designed into SPOT+ results in considerable complexity, but it has paid off well in standardization of testers. Increased up time and ease of maintainability are two unforeseen benefits that have emerged. SPOT+ systems are now used throughout HP in sites as diverse as San Diego, Corvallis, HP Laboratories in Palo Alto, and Singapore.

Drop Detection

Many HP print cartridge testers need to verify that drops are being fired. This is done by means of an optoelectronic drop detector as outlined in Fig. 4.

The bulb, the lens and the detector establish the optical path. To a first approximation, all the light that travels from the bulb and reaches the lens is collected at the detector.

The test controller (not shown) causes a single nozzle of the print cartridge to eject drops, provided, of course, that the nozzle does in fact work. The ejected drop passes through the optical path, causing a reduction of the flux of light from the bulb to the detector. The output signal of the detector is fed to a data acquisition board of the test controller. The signal processing software in the test controller produces a simple yes/no indication with a small but specified probability of error.

There are several requirements for the optical path. The sensitive area covered by the optical path must be large enough to cover the entire nozzle plate. Otherwise, a positioning mechanism would be necessary to align the sensitive area of the optical path with the nozzle to be tested. Since a typical tester contains many print cartridge test stations this would be a complex and expensive proposition.

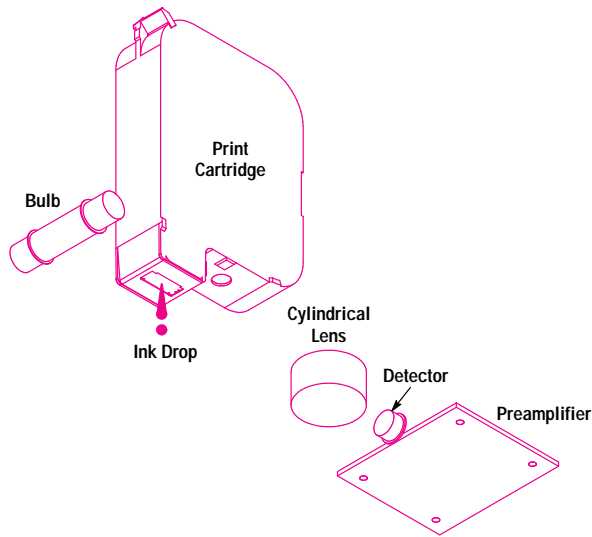


Fig. 4. Drop detector components.

Furthermore, the change of light flux must be rather independent of the trajectory of the passing drop. Otherwise, certain nozzles that produce unacceptable drops might be classified as functional while others that produce small but acceptable drops might be classified as nonfunctional.

Finally, the optical path components should be simple, small in number, and easy to assemble. The design shown in Fig. 4 fulfills all these requirements.

Fig. 5 shows an example of a computer simulation of the flux change or sensitivity α as a function of the drop location (x_0, y_0) . The left side is nearest the bulb and the right side is nearest the lens. The sensitivity varies significantly, but it is possible to select zones that are quite usable for our purposes. First, there is a rather flat zone next to the bulb and secondly, there are ridge lines of nearly constant sensitivity straddling the peak parallel to the optical axis (x axis). If the optical path is laid out properly, the flat part provides a large zone of somewhat low sensitivity. If the nozzles of the print cartridge happen to be arranged in two columns, one can lay out the optical path so that these columns coincide with two ridge lines of the same nearly constant sensitivity. In this case, one can achieve both constancy and a high value of the sensitivity α .

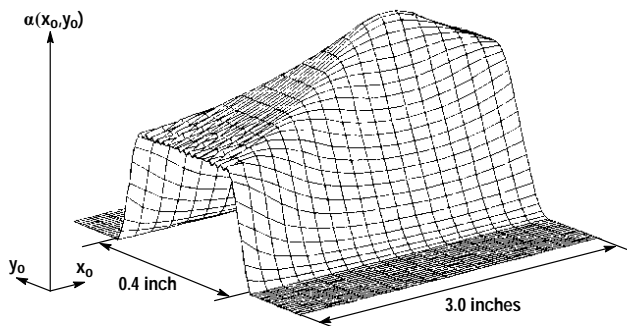


Fig. 5. Sensitivity of the drop detector as a function of drop position.

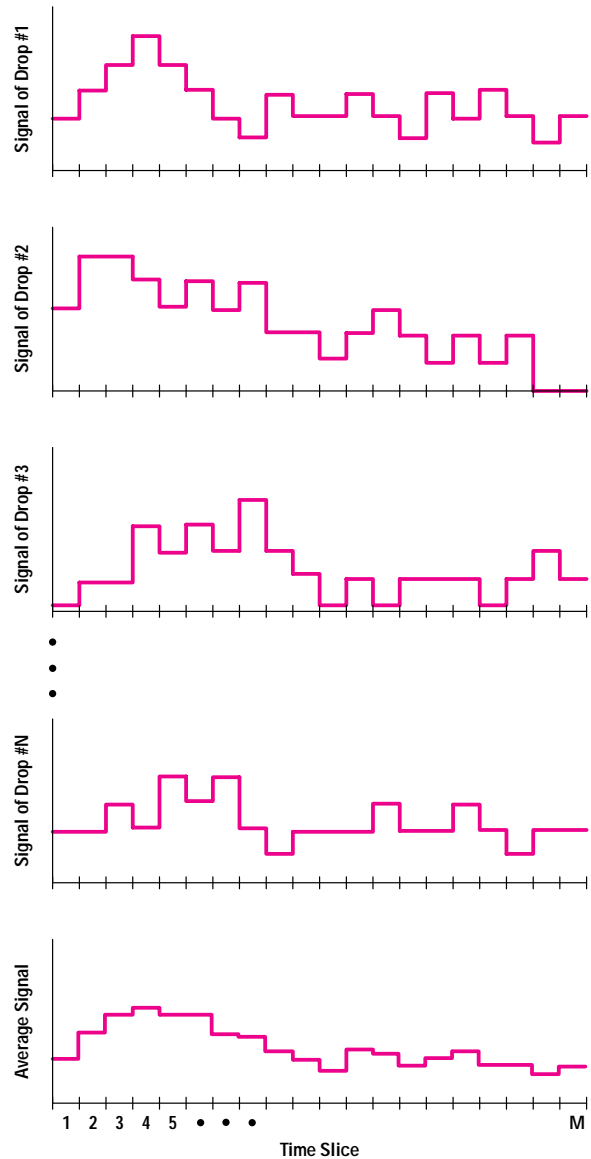


Fig. 6. Averaging of the drop detector output signals for several drops reduces noise and produces a signal that can be interpreted.

Even with an optimized optical path, the detector output signal is rather noisy. The noise comes from jitter in the drop generation process, mechanical and electrical noise, extraneous light, $1/f$ noise of the detector, and other sources.

Fig. 6 demonstrates the method used to minimize the influence of noise. Since the noise sources are almost entirely uncorrelated with each other and with the drop signal, the averaging of several signals reinforces the signal in proportion to the number of signals averaged, while the noise will grow only as the square root of that number. Therefore, the ratio of signal to noise improves as the square root of the number of signals averaged. Several metrics of the averaged signal can be employed to arrive at the desired decision. Level triggering, peak-to-peak value, and rms value have all been successfully used.

Acknowledgments

The idea of architecting the print cartridge assembly line around a common tooling platform was the result of the creative contributions of many people. The authors would like to thank Tim Carlin, Jim Sykora, Roy Pilcher, Carol Beamer, and Deb Hockley for their early efforts which helped to catalyze the tooling platform concept. The efforts of Mick Trego, Hanno Ix, and Dave Etherton made automated testing of the DeskJet 1200C print cartridges a reality. The individual process and manufacturing engineers are due a great deal of credit for tolerating the many surveys and meetings that provided us with the information needed to help make the automated assembly system a success.

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Connectivity of the HP DeskJet 1200C Printer

The connectivity components include the language firmware, a language interface to the mechanical firmware, software printer drivers, and tools for various environments and for driver developers. A screen calibrator tool enlists the user's help in making the printed output match the screen.

by **Anthony D. Parkhurst, Ramchandran Padmanabhan, Steven D. Mueller, and Kirt A. Winter**

"Connectivity" is the term used to refer collectively to the software and firmware components of the HP DeskJet 1200C printer that, along with the printer itself, bring to the user a complete color printer solution. These components are the language firmware, a language interface to the mechanical firmware, software printer drivers and other tools for the Microsoft® Windows and Macintosh environments, and software tools for MS-DOS® driver developers.

The language, PCL 5C, is a colorized and (continually) enhanced version of the highly efficient printer command language developed internally by HP to provide consistent feature support across its printer product lines, from the DeskJet to the PaintJet to the LaserJet lines. The language system interface to the mechanical firmware is a well-defined interface that allows outside language firmware developers, such as Adobe Systems, to develop other language processes besides PCL, such as PostScript™ for the printer. HP printer drivers are written for the Windows and Macintosh environments, and include highly advanced color management tools that allow the user to achieve the best color quality available in the DeskJet 1200C. These color management tools are also available to independent software vendors developing DOS drivers for the printer. Topics discussed in this article are:

- The PCL 5C language firmware
- Raster operations, a PCL 5C language feature that provides advanced drawing functionality for the printer driver
- The language interface to the mechanical firmware, hereafter called the language interface
- A screen calibration tool for color management.

PCL 5C Language Firmware

The HP DeskJet 1200C printer unifies HP LaserJet printer intelligence with high-quality color printing by combining a new generation of inkjet technology with a color enhanced version of the LaserJet language known as PCL 5C. PCL 5C gives applications access to state-of-the-art font scaling technologies (Intellifont and TrueType™), full-featured vector graphics with the HP-GL 2 language, and 24-bit color imaging.

The programming, or firmware, in the DeskJet 1200C contains a PCL 5C page formatter subsystem and a subsystem to control the hardware and electronics. The PCL 5C page formatter converts the high-level data stream from the

computer into a simple data stream for the print engine. This interpreter consists of two processes: the parser and the image processor.

Parser

The parser recognizes commands in the data stream and performs the requested functions. The output of the parser is a *display list* that is sent to the image processor. PCL 5C is a *page description language*: the data stream describes what the page should look like and prints the page when it is complete. Page description consists of objects combined with colors and patterns. An obvious benefit of a page description language is that the objects do not have to be created in a position dependent order (e.g., top to bottom), so the host need not merge or reorder objects before sending them. The kinds of objects used in PCL 5C are text, rules (rectangles), HP-GL 2 graphics (vectors and polygons), and images (see Fig. 1).

After specifying character position on the page, the typeface desired, and the point size (72 points/inch), the application sends character codes to create text. The parser generates a bitmap of the requested character from a scalable typeface and stores the bitmap into the display list with the appropriate positioning information. If this identical character is requested later in the job (which is common for English text), the bitmap is reused. PCL 5C can scale characters from $\frac{1}{4}$ point to $999\frac{3}{4}$ points with astonishing quality.

Rules, which are simply rectangles, are stored on the display list as a starting coordinate pair along with a width and a height.

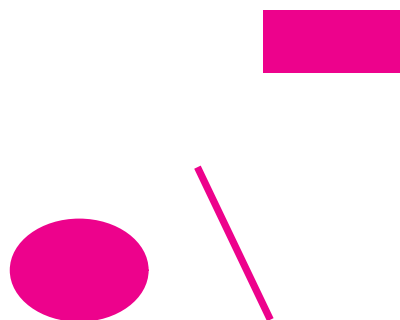


Fig. 1. Basic object types: text, rules, polygons, vectors, and raster.

HP-GL 2, the vector graphics language for pen and large-format plotters, is a subparser within PCL 5C. HP-GL 2 has features that provide high-level graphics, including polygons. All HP-GL 2 objects are scaled, clipped, and decomposed into simple vectors and trapezoids to be stored on the display list. An additional feature of HP-GL 2 within PCL 5C is the ability to use outlines from the font scaling technology directly as polygons. This gives the application the ability to create special effects with text.

All of these objects are basically colorless—on a monochrome printer such as a LaserJet, they will print as black. The parser treats them as black objects. Color is handled independently and is not applied to these objects until they get to the image processor. To work with color, the application must first configure a color palette. For compatibility with monochrome printers, the default palette is defined as having two colors: black and white. Palette configuration is performed in three steps. First, the size and color space of the palette are defined. Next, each entry of the palette is assigned a color in that color space (up to 24 bits of color information per entry). Finally, color can be adjusted for gamma correction and rendering algorithm. Color can be used as foreground color for objects such as text and vectors, in color patterns, and in raster images. When such a color is selected, the parser stores the color on the display list, and the image processor will apply this color to each of the objects on the display list until another color is selected. Another method of using color is to define a color pattern to apply to the objects. A color pattern differs from foreground color in that several colors can be specified within the pattern. The parser stores this pattern on the display list for the image processor to apply to objects. The third and final way to use color is raster images.

Raster processing in PCL 5C is very flexible, but most applications send raster data in one of four ways. Images can be sent as single-plane bitmaps (monochrome), which are LaserJet-compatible. Color can be applied to these bitmaps in the same way as other black objects. Another form of raster is 3-plane simple color. This mode is for applications that do most of the work themselves and prefer to simply send a color bitmap. Each pixel can take on eight values to represent the colors that the print engine can print (black, red, green, blue, cyan, magenta, yellow, and white). For higher-level applications, data is represented as 8 bits per pixel, indexed. Each pixel can have a value from 0 to 255, and that value is used to index into a palette where each entry is a color defined in a 24-bit color space. Finally, for the highest-quality images from color scanners, data can be sent directly as 24 bits per pixel. Palette entries are not used for this mode. Standard techniques (dithering and error diffusion) are used to reduce the continuous-tone image to 3-plane simple color for the print engine. The resulting image is stored in the display list.

The Image Processor

The image processor takes objects from the display list, applies colors or patterns and puts them in *swaths*. On this printer, swaths consist of three bitmaps, one each for cyan, magenta, and yellow. Swaths are 2464 dots wide by 128 dots high and are used by the print engine to drive the inkjet printheads. The width of the swath is determined by the printable area of the largest supported media size, and the

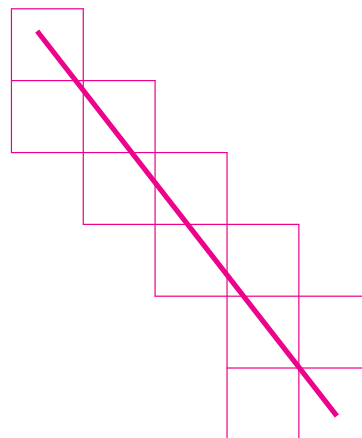


Fig. 2. Precomputed tiles are used to create a vector.

height is established by performance and efficiency issues. Although text and raster are fully formed bitmaps at this point, rules, HP-GL 2 vectors, and trapezoids are simply coordinate pairs. The image processor must create bitmaps for these objects. Rules are simple, since they are rectangles that lie horizontally or vertically, but vectors and trapezoids are not so well-behaved. There are well-established vector-to-raster conversion algorithms, but the DeskJet 1200C uses a high-performance vector-to-raster conversion process developed for HP large-format electrostatic plotters.¹ This method uses precomputed bitmap tiles stored in ROM to build vectors (see Fig. 2). Tiles are bitmaps that are aligned to word boundaries and can be pasted as needed in the swath. The image processor selects the tiles based on slope, width and position of the vector relative to word (16-bit) boundaries.

At this point, all the objects (text, rules, tiles, images) look like bitmaps. To complete this architecture, colors and patterns on the display list are also tile bitmaps. Similar to vector-to-raster tiles, these tiles can be pasted anywhere in the swath along word boundaries. When a foreground color is selected, the parser gets the color value from the palette, then applies the current dither matrix to create a 16-by-16-bit color tile (the size of the dither matrix is 16 by 16 bits) which is stored on the display list as a three-plane object: one plane each for cyan, magenta, and yellow. When the image processor needs to apply a color tile to an object, the color tile is logically replicated to cover the page, then combined or masked with the object, and the result is put in the swath (Fig. 3). A monochrome pattern in effect at this time will also be combined with the object. A color pattern differs from a monochrome pattern in that the color pattern already has color applied to it. The logic used in combining color tiles, pattern tiles, object bitmaps, and the destination bitmap (swath) is selected by the application and explained in “Raster Operations” below. When all the objects for each swath are processed, the swath is printed.

An alternative to the display list would be a frame buffer, which is a full-page bitmap used to create the final output. Although this approach has its advantages (especially with very complex graphics), it consumes far more memory than most jobs require. The display list’s efficient use of memory allows the printer firmware to work farther ahead of the print engine, providing smooth and rapid printing.

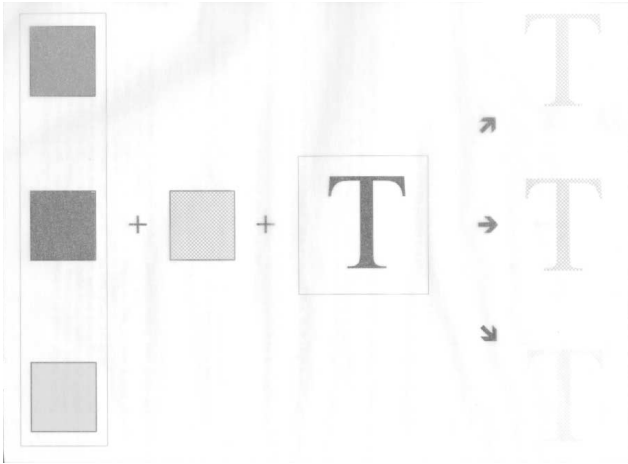


Fig. 3. The cyan, magenta, and yellow color components are combined with the pattern and bitmap.

Is all this functionality worth the extra product cost to provide it? Yes. With a high-level language like PCL 5C, the printer can do much of the work that the host computer would have to do for a bare raster printer. This allows the host computer to service the user instead of the printer. Because the DeskJet 1200C is LaserJet-compatible, LaserJet applications continue to work for the DeskJet 1200C, and driver writers simply have to add color functionality to their LaserJet drivers instead of having to create yet another printer driver from scratch.

Raster Operations

The world of graphical output devices is divided into two distinct categories: raster devices and vector devices. Most color and laser printers are raster devices, although graphic applications communicate with them through high-level page description languages. This provides a level of abstraction away from hardware, allowing the applications to specify attributes and lay down geometrical shapes in a device independent fashion. Although the device uses pixels for its final graphic representation, applications do not need to talk to the interface in terms of pixels. For instance, an application can take advantage of the fact that the printer can draw circles by just sending down a radius and the coordinate position of the center instead of every point on the circumference. The application can also specify a fill pattern for the object and lay it along with or on top of similar objects, blending their corresponding textures in several different ways.

Microsoft's Graphical Device Interface (GDI) is a suite of interface specifications that bridges the gap between various Windows-based GUI (graphical user interface) applications and a wide range of graphical output devices. GDI is a high-level interface to a graphical output device. The HP DeskJet 1200C driver for Microsoft Windows applications can directly map several GDI primitives and drawing modes to PCL 5C and HP-GL 2 high-level object descriptions. A commonly used parameter in many GDI primitives is called a logical operation or a *raster operation* (ROP).

ROPs are drawing modes that define how the bitwise interaction between a high-level source object, a color texture, and the current destination produces a new destination.

Examples of source objects are vectors, polygons, text, and raster images. Texture is a color or monochrome mask that is applied to the source in a manner specified by the ROP. Some applications have objects whose color is based not only on the currently selected foreground color, but also on the original contents of the destination.

Theory of ROPs

ROPs directly affect the appearance of objects drawn on the display device by making use of both the selected foreground color and the current contents of the destination. For instance, an object can be placed on top of another object so that it either completely overlaps its destination area or its colors merge with those of the underlying object. The drawing mode specified by the ROP makes it possible to choose one of the several alternatives for rendering the object by defining a bitwise Boolean operation between the pixels of the source and the pixels of the destination.

Consider a monochrome device in which an object can be drawn only with a black print cartridge on a destination whose pixels are either black or white. There are four ways of combining a black or white source pixel with a black or white destination pixel.

```
Source    1 1 0 0
Destination 1 0 1 0
```

where 0 is black and 1 is white.

A bitwise Boolean operation for each of the above four cases can yield either a 0 or a 1 in each of the four bit positions. This results in 16 two-operand ROPs. These are the monochrome drawing modes. A complete list of monochrome drawing modes is shown in Table I.

| Table I | | | |
|--------------------------|------------|--------------|---------------|
| Monochrome Drawing Modes | | | |
| Source (S) | 1 1 0 0 | Monochrome | |
| Destination (D) | 1 0 1 0 | Drawing Mode | |
| Result | 0 0 0 0 | 0 | BLACK |
| | 1 0 0 1 | ~(S D) | NOT_MERGE_PEN |
| | 2 0 0 1 0 | ~S & D | MASK_NOT_PEN |
| | 3 0 0 1 1 | ~S | NOT_COPY_PEN |
| | 4 0 1 0 0 | S & ~D | MASK_PEN_NOT |
| | 5 0 1 0 1 | ~D | NOT |
| | 6 0 1 1 0 | S ^ D | XOR_PEN |
| | 7 0 1 1 1 | ~(S & D) | NOT_MASK_PEN |
| | 8 1 0 0 0 | S & D | MASK_PEN |
| | 9 1 0 0 1 | ~(S ^ D) | NOT_XOR_PEN |
| | 10 1 0 1 0 | D | NOP |
| | 11 1 0 1 1 | ~S D | MERGE_NOT_PEN |
| | 12 1 1 0 0 | S | COPY_PEN |
| | 13 1 1 0 1 | S ~D | MERGE_PEN_NOT |
| | 14 1 1 1 0 | S D | MERGE_PEN |
| | 15 1 1 1 1 | 1 | WHITE |

The symbols ~, ^, &, and | represent the bitwise logical operations NOT, exclusive-OR (XOR), AND, and OR, respectively.

Color Drawing Modes

When color is introduced into the device, both the source and the destination have three planes of data representing eight primary colors: the additive colors red, green, and

blue, the subtractive colors cyan, magenta, and yellow, and black and white. Here the monochrome ROPs are performed separately for each of the three planes to arrive at the consolidated resultant destination.

At any level of drawing, solid geometrical objects are drawn as outlines and filled with a color pattern using a brush. It is no different in computer graphic art packages. A color pattern generated by a brush is called a texture. Textures are normally masked through solid objects and placed in their final destinations. The drawing modes must support an additional parameter because there is more than one way to make use of a texture brush. The color drawing modes consist of a set of three-operand ROPs that combine the pixels of source, texture, and destination to produce new destination pixels. There are eight ways of grouping a Boolean source, texture, and destination pixel on a single plane:

| | |
|-------------|-----------------|
| Texture | 1 1 1 1 0 0 0 0 |
| Source | 1 1 0 0 1 1 0 0 |
| Destination | 1 0 1 0 1 0 0 0 |

Extrapolating our derivation of monochrome drawing modes to the color case results in 256 possible ways of combining source, texture, and destination to produce a new destination. ROPs on color data are performed on a plane-by-plane basis. Some of the most commonly used ROPs are shown in the following table.

Table II
Color Drawing Modes in RGB Space

| Texture (T) | 1 1 1 1 0 0 0 0 | Color |
|-----------------|---------------------|----------------------|
| Source (S) | 1 1 0 0 1 1 0 0 | Drawing |
| Destination (D) | 1 0 1 0 1 0 1 0 | Mode |
| Result | 0 0 0 0 0 0 0 0 | 0 DARKNESS |
| | 51 0 0 1 1 0 0 1 1 | ~S NOT_SOURCE_COPY |
| | 85 0 1 0 1 0 1 0 1 | ~D DEST_INVERT |
| | 90 0 1 0 1 1 0 1 0 | T ^ D TEXTURE_INVERT |
| | 102 0 1 1 0 0 1 1 0 | S ^ D SOURCE_INVERT |
| | 136 1 0 0 0 1 0 0 0 | S & D SOURCE_AND |
| | 168 1 0 1 0 1 0 0 0 | (T S)&D |
| | 192 1 1 0 0 0 0 0 0 | T & S MERGE_COPY |
| | 204 1 1 0 0 1 1 0 0 | S SOURCE_COPY |
| | 234 1 1 1 0 1 0 1 0 | (T&S) D |
| | 240 1 1 1 1 0 0 0 0 | T TEXTURE_COPY |
| | 252 1 1 1 1 1 1 0 0 | T S |
| | 255 1 1 1 1 1 1 1 1 | 1 BRIGHTNESS |

A complete list of the 256 color drawing modes can be found in the programmer's reference manual of the Microsoft Windows software development kit and also in the HP DeskJet 1200C developer's guide.

Tables I and II show ROPs defined in RGB color space, whereas the DeskJet 1200C printer operates in a CMY color space (using cyan, magenta, and yellow print cartridges). The image processing firmware in the printer renders objects in CMY space and generates C, M, and Y planes of destination bitmaps. Users, however, being more used to the screen-oriented RGB model, send down RGB data that defines ROPs in RGB color space. The ROPs, therefore, have to be translated into CMY space for the image processor. Since RGB and CMY data complement each other, they can

be converted easily from one to another. The ROP is transposed by toggling and swapping the bits within the byte so as to preserve the interpretation of the corresponding bitwise logical operation. ROPs defined in Table II are in RGB color space. Table III provides the CMY translation.

Table III
Color Drawing Modes in CMY Space

| Texture (T) | 1 1 1 1 0 0 0 0 | Color |
|-----------------|---------------------|--------------|
| Pen Source (S) | 1 1 0 0 1 1 0 0 | Drawing |
| Destination (D) | 1 0 1 0 1 0 1 0 | Mode |
| Result | 255 1 1 1 1 1 1 1 1 | 1 DARKNESS |
| | 51 0 0 1 1 0 0 1 1 | ~S |
| | 85 0 1 0 1 0 1 0 1 | ~D |
| | 165 1 0 1 0 0 1 0 1 | ~(T ^ D) |
| | 153 1 0 0 1 1 0 0 1 | ~(S ^ D) |
| | 238 1 1 1 0 1 1 1 0 | S D |
| | 234 1 1 1 0 1 0 1 0 | (T&S) D |
| | 252 1 1 1 1 1 1 0 0 | T S |
| | 204 1 1 0 0 1 1 0 0 | S |
| | 168 1 0 1 0 1 0 0 0 | (T S)&D |
| | 240 1 1 1 1 0 0 0 0 | T |
| | 192 1 1 0 0 0 0 0 0 | T & S |
| | 0 0 0 0 0 0 0 0 | 0 BRIGHTNESS |

ROPs and the PCL Print Model

The original PCL 5 print model specifies how to fill source image objects with any of the printer's predefined, shaded, hatched, or user-downloaded patterns. In addition to source, pattern, and destination, source and pattern transparency modes must be considered when masking the source image through the pattern tile onto the destination. Source transparency mode specifies whether the white pixels of the source image are transparent or opaque. Pattern transparency provides a similar definition for the white pixels of the pattern. Depending on the transparency modes, the destination either shows through the transparent pixels or gets blocked by the corresponding white pixels. PCL 5C also has a foreground color definition that gets applied to a monochrome pattern to generate what is known as a texture. A texture is either a color pattern or a colorized monochrome pattern (a monochrome pattern with foreground color applied to it).

PCL 5C implements a new print model, which performs transparency mode operations before it does ROPs.

ROP Formulas

We shall now proceed to derive the formulas used by the image processor to render objects into three-plane CMY bitmaps.

The main entities used are defined as follows:

Operands

- Source: Character cell, rules, color and monochrome raster images, HP-GL 2 vectors and polygons
- Texture: Either color pattern or (foreground color & pattern mask)
- Destination: Bitmaps for the C, M, and Y planes.

Operators

Source transparency and pattern transparency definitions, which generate a transparency mask
Color drawing modes (i.e., ROPs), which operate on the above three operands.

Notation

~Source denotes the white pixels of the source.
~Pattern denotes the white pixels of the pattern.

In a color source image, ~Source would be the white extract from the three planes of consolidated source data.

The generic formula used by the image processing firmware is based on the following premises:

- The destination shows through the white areas of the source if source transparency is on.
- The destination shows through the white areas of the pattern in the source area if pattern transparency is on.
- For all nonwhite pixels, the ROP result of the texture, source, and destination is the new destination.

$$\text{Destination} = (\text{Destination} \& \text{Transparency_Mask}) \mid (\text{ROP Result} \& \sim(\text{Transparency_Mask})),$$

where Transparency_Mask has to be defined for the four basic interactions of source and pattern transparencies with ROPs.

For the sake of simplicity, the default ROP has been chosen in Figs. 4, 5, 6, and 7. It is defined as (Texture OR Source) and converted to (Texture AND Source) in CMY space. These illustrations follow the CMY nomenclature.

Source Opaque and Pattern Opaque (Fig. 4). At present, this is the most commonly used model because most of the Windows GDI applications do not use the PCL transparency modes. Source and pattern transparencies are set to opaque and the transparency functionality is achieved using ROPs.

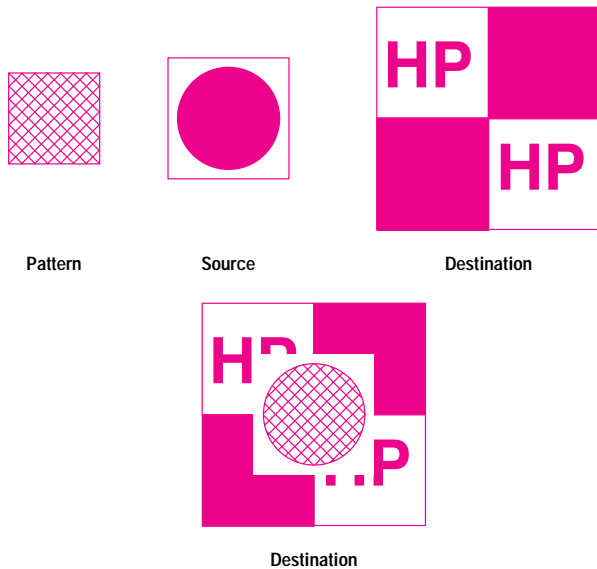


Fig. 4. The source opaque and pattern opaque transparency mode for the default raster operation.

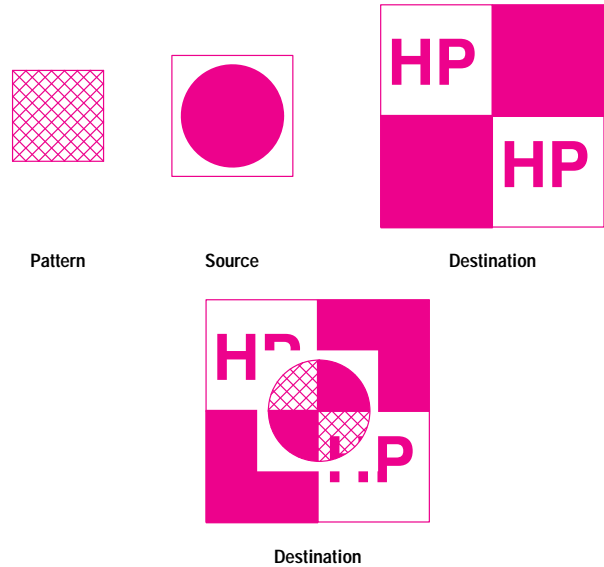


Fig. 5. The source opaque and pattern transparent transparency mode for the default raster operation.

$$\text{Transparency_Mask} = 0$$

$$\text{Destination} = \text{ROP}(\text{Texture}, \text{Source}, \text{Destination})$$

Source Opaque and Pattern Transparent (Fig. 5). Since the pattern is transparent, the destination shows through the white areas of the pattern where the corresponding source pixels are nonwhite. However, the white area of the source is written onto the destination because the source is opaque. The result of the ROP is applied to the source pixel area of the destination, allowing the destination to show through the transparent source pixel area of the pattern.

$$\text{Transparency_Mask} = (\text{Source} \& \sim\text{Pattern})$$

$$\text{Destination} = (\text{Destination} \& (\text{Source} \& \sim\text{Pattern})) \mid (\text{ROP}(\text{Texture}, \text{Source}, \text{Destination}) \& \sim(\text{Source} \& \sim\text{Pattern}))$$

Source Transparent and Pattern Opaque (Fig. 6). The destination shows through the white areas of the source mask. The source pixel area of the destination is cleared and the result of the ROP is laid down.

$$\text{Transparency_Mask} = \sim\text{Source}$$

$$\text{Destination} = (\text{Destination} \& \sim\text{Source}) \mid (\text{ROP}(\text{Texture}, \text{Source}, \text{Destination}) \& \text{Source})$$

Source Transparent and Pattern Transparent (Fig. 7). This is the default case in the PCL 5C print model, and therefore the default case in the printer. The destination shows through the transparent area of the source. The destination also shows through the transparent area of the pattern tiled across the source. The result of the ROP is applied to the intersection of the source and the pattern. This ensures that the transparent areas of the source and pattern do not affect the destination.

$$\text{Transparency_Mask} = \sim(\text{Source} \& \text{Pattern})$$

$$\text{Destination} = (\text{Destination} \& \sim(\text{Source} \& \text{Pattern})) \mid (\text{ROP}(\text{Texture}, \text{Source}, \text{Destination}) \& (\text{Source} \& \text{Pattern}))$$

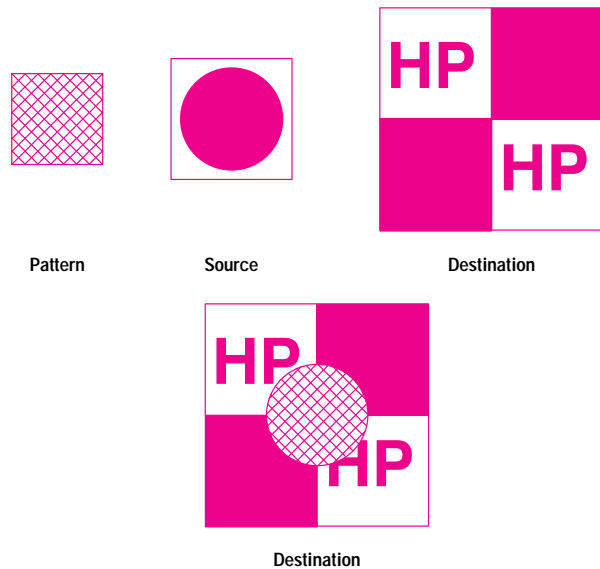


Fig. 6. The source transparent and pattern opaque transparency mode for the default raster operation.

Applications of ROPs

One typical application of ROPs is to clip objects to arbitrary clip paths. Consider an example of drawing an arbitrarily shaped object with a radial gradient texture. Fig. 8 shows the various steps taken to achieve this.

First the application sends down several concentric rings, each with a different shade of color. These are applied to the destination using ROP 90 (Destination = Destination XOR Texture), resulting in a circular gradient texture as shown in Fig. 8a.

The second step places a solid black arbitrarily shaped object (Fig. 8b) on top of the gradient using ROP 204 (Destination = Source). This results in Fig. 8c.

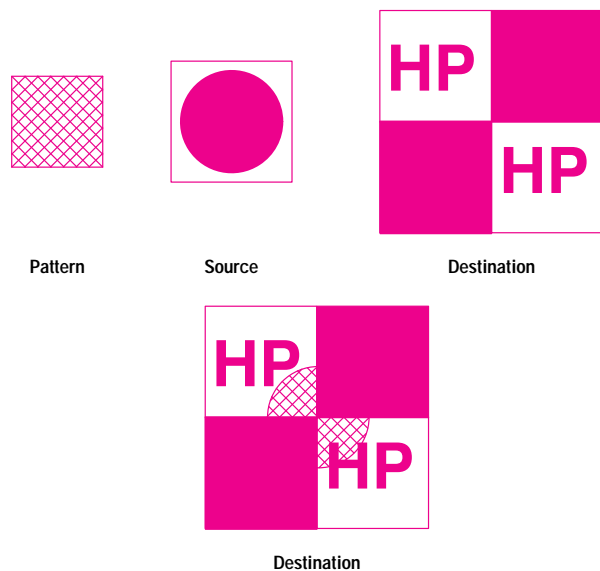


Fig. 7. The source transparent and pattern transparent transparency mode for the default raster operation.

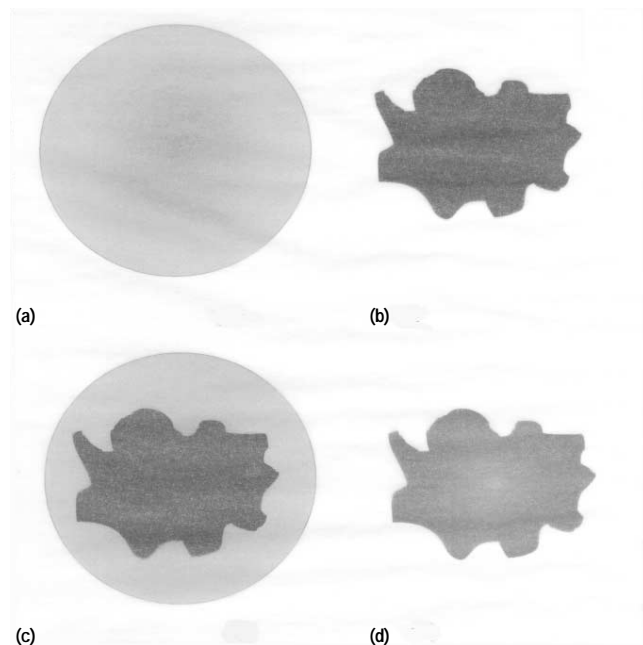


Fig. 8. Using raster operations to draw an arbitrarily shaped object with a radial gradient texture.

The final step sends the complete set of concentric rings all over again using ROP 90. This serves to erase the gradient pixels external to the object, resulting in the required radial gradient shading clipped to the arbitrary shape as in Fig. 8d.

Fig. 9 shows the result of a similar operation involving gradient-shaded text objects.

Pixel Placement Precision

Color space and address space are two fundamental differences between display devices and hard-copy devices. RGB-to-CMY conversion between screen-oriented applications and color printers has already been mentioned earlier in this article. Another area of incompatibility is the location of a pixel in the coordinate system. The printer places pixels at the intersections of the squares of a theoretical, device dependent grid covering the printable area of the page, whereas CRTs place pixels at the centers of the squares. These two pixel placement methods are called the *grid-intersection* method and the *grid-centered* method. They are shown in Figs. 10a and 10b, respectively.

A problem arises in the grid-intersection model when two adjacent polygons are defined and the ROP chosen performs an exclusive-OR operation on the polygons and the destination. The pixels along the border may be rendered twice, resulting in stray marks of a different color along the polygon edges. This looks very bad on the printed output because applications normally define complex graphical images using several little polygons of different shades of color.

The PCL 5C implementation in the DeskJet 1200C printer provides a choice of pixel placement methods. The default grid-intersection model places pixels at the intersections of the device dependent grid. A new grid-centered model simulates placing the pixel at the center of the square in the grid



Fig. 9. The result of an operation similar to Fig. 8 involving gradient-textured text.

by not rendering the last row and last column of every pixel in a polygon defined under that model. For example, the grid-centered model of a rectangle from (1,1) to (3,4) is rendered as shown in Fig. 11.

The DeskJet 1200C printer also makes use of a high-precision polygon decomposition algorithm to break up complex user-defined polygons into simpler trapezoids and rectangles for the image processor to render using ROPs. The need for a high-precision polygon decomposition is mandated by the same set of problems that required an alternative pixel placement model. The polygon decomposition algorithm ensures that every polygon pixel is defined once and only once by maintaining integral and fractional pixel coordinate information to the desired level of precision.

Fig. 12 shows four adjacent rectangular patterns rendered using the ROP (Destination XOR Texture) under both of the pixel placement models. The overlapping pixels create extra

black lines along the adjacent borders of the rectangles in the grid-intersection model. The problem is solved in the grid-centered model.

Predictable Rendering

When using ROPs to clip to an arbitrary path, it is not only necessary to be precise in physical pixel placement, but it is also necessary to render the objects in a predictable manner. In Fig. 13, a raster image has been rendered using a technique called *error diffusion*. Error diffusion takes an input raster image (each pixel can be defined as a 24-bit RGB color) and produces the output raster data in terms of dots on the physical printer destination. The output raster data is generated by looking at each pixel color and then propagating to the surrounding pixels the difference between the original color and the rendered physical color. In some implementations of error diffusion, a random factor is added to avoid any repeatable patterns in the output raster image. In these implementations, the same input raster image can produce a different output raster image every time it is rendered.

In Fig. 13, the raster image is being clipped into an oval shape in the same manner that the gradient shade was clipped in Fig. 8. The raster image is rendered and placed on top using ROP 90, then a black oval is placed on top using ROP 204, and finally, the image is rendered again onto the destination using ROP 90 (the outline of the oval is sent down separately from this clipping process). Fig. 13a shows what happens using error diffusion with a random factor. Rendering the raster image does not necessarily produce exactly the same raster output each time. Outside the black oval area, the image is not completely erased and will produce unpredictable results that appear as a ghost image of the original full raster image. Fig. 13b shows the desired

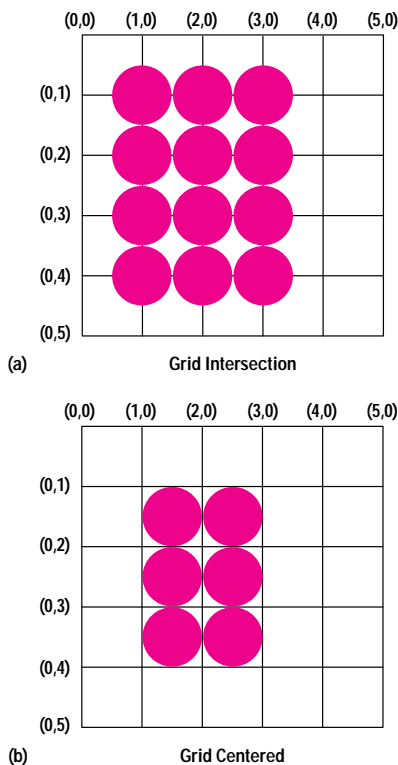


Fig. 10. Pixel placement methods. (a) Grid-intersection. (b) Grid-centered.

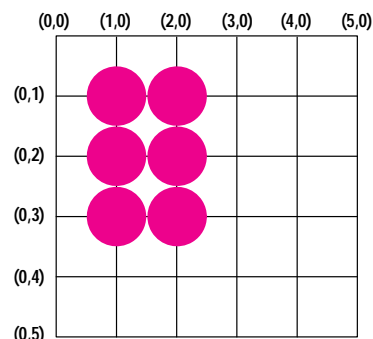


Fig. 11. Grid-centered model of a rectangle from (1,1) to (3,4).

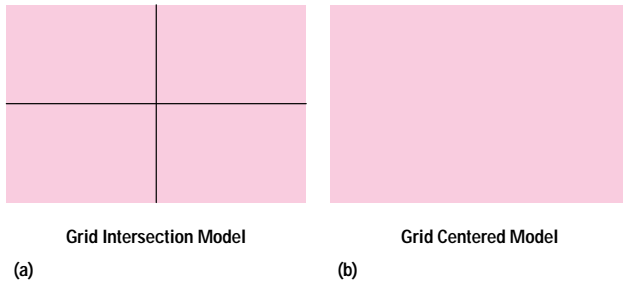


Fig. 12. (a) Rendering four adjacent rectangle patterns using the grid-intersection method results in extra black lines. (b) The problem is solved using the grid-centered method.

result when the output image is rendered in a way that is predictable and the image is completely erased outside of the oval.

Language Interface

For the sake of modularity and reuse, the HP DeskJet 1200C printer firmware is subdivided into major subsystems. Printer system “glue logic” firmware holds these subsystems together. The major subsystems include:

- Front-panel subsystem
- I/O subsystem
- Print engine subsystem
- Nonvolatile memory subsystem
- Printer Job Language (PJL) subsystem
- PCL and PostScript language subsystems.

Each subsystem is characterized by its own well-defined interface. The printer system is an amorphous entity with which each subsystem interacts. Thus, the printer system is

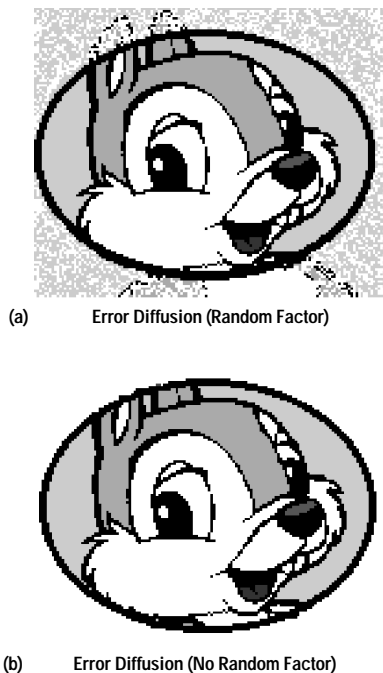


Fig. 13. (a) Some implementations of error diffusion add a random factor, which can result in unpredictable ghost images when raster operations are performed. (b) Omitting the random factor results in predictable imaging.

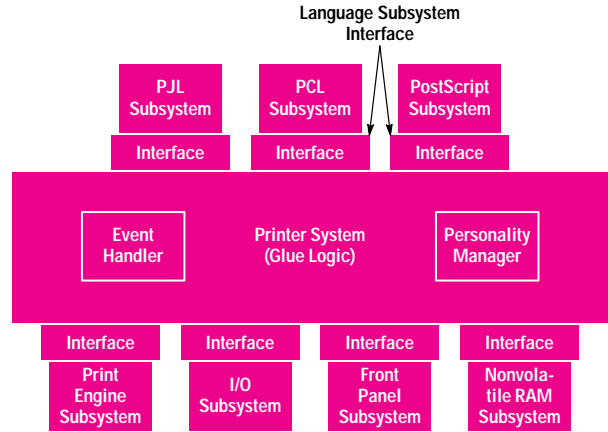


Fig. 14. HP DeskJet 1200C printer firmware architecture.

the mortar that holds the various subsystems together. It is thick in some places and thin in others, depending on how closely the subsystem interfaces line up. Two other blocks of firmware—the personality manager and the event handler—are not subsystems in a strict sense, since they lack their own well-defined interfaces. Instead, they use the interfaces of other subsystems. However, they are significant enough areas of the printer system that they are often referred to separately. Fig. 14 depicts the DeskJet 1200C printer firmware architecture.

The key subsystem in this architecture, in terms of connectivity, is the language subsystem. The DeskJet 1200C PS printer has two language subsystems: PCL 5C and PostScript Level 2. The language subsystem is the most significant because it indirectly interacts with all of the other subsystems, as well as the event handler and the personality manager. The interface between the language subsystem and the printer system, which we will call the *language interface*, is the subject of this section of this article.

At the most basic level, a language subsystem is an organized piece of software that accepts input language data from the printer system, interprets it, and produces a bitmap representation of an image, which is passed to the printer system to be transferred to the output media. In this respect, the language subsystem deals with I/O access for language parsing and with the print engine for imaging. The language subsystem is also involved in other interactions with the printer system such as personality management, access to nonvolatile memory, printer reconfiguration, printer system events and status, and language subsystem events and status.

Both PCL 5C and PostScript fit this definition of a language subsystem. The language interface was therefore designed to accommodate both. This has tremendous advantages. The overhead of having to maintain two different interfaces is eliminated. The printer system code in nearly all cases behaves identically regardless of whether the active language is PCL 5C or PostScript. This reduces the complexity of the printer system code. There is also only one language subsystem interface specification to maintain. Balancing the needs of PCL 5C and PostScript has been easy. There are only a few spots in the language interface that are specific to only one language.

| Service Call | Description | When Called (Typically) |
|---------------------|---|---|
| lang_init_req | Requests initialization of the language subsystem | System (re)initialization |
| enter_lang | Requests that the language become the interpreter of the input data stream. | Printer system determines the input stream belongs to the language. |
| lang_die | Requests language finish all imaging, free all resources, delete all processes, and otherwise prepare to die. | Printer system determines the input stream belongs to a different language. |
| media_fed | Acknowledges feed_media call. Indicates media is fed. | Printer system completes media loading. |
| swaths_imaged | Acknowledges swaths on image call have been imaged. | Printer system completes transfer of image to media. |
| async_periph_status | Notifies language of a change in peripheral status such as online, jam, etc. | Printer system has a change in status. |

Fig. 15. Interface library routines provided by the language subsystem.

At the code level, the language interface consists of an information window and an interface library. The information window is a shared global data structure containing mostly static information about each side of the interface. The interface library contains two sets of routines. One set is provided by the language subsystem for the printer system to call. The other set is provided by the printer system for the language subsystem to call.

The information window and the interface library alone do not make the language interface complete. The language interface specification also includes a model-of-use section, which describes how the information window and interface library routines are used throughout various phases of print job execution. There is also a detailed section on media handling and imaging.

The information window for the DeskJet 1200C printer contains such items as: printer status, default image settings

(paper size, character set, etc.), supported sources (input trays), destinations (output trays), and media sizes, as well as the printer's network name and type. The interface library contains the routines that handle the language subsystem's interactions with personality management, I/O access, imaging, status and events, and other interactions. Figs. 15 and 16 depict the two sets of routines that make up the interface library.

Model-of-Use Description

To best make use of the resources available, the primary one being RAM available to the language, the DeskJet 1200C printer system only has one language subsystem initialized at any given time. After power-on, the information window is initialized, and the printer goes online for the first time with no language subsystem initialized. When a print job enters the printer, the personality manager, with help from the printer job language subsystem, determines which

| Service Call | Description | When Called (Typically) |
|---------------------|---|--|
| lang_init_rsp | Acknowledges lang_init_req call. Ready to interpret data. | Language subsystem completes initialization. |
| get_input | Requests an input data buffer | Language parsing input data. |
| return_io_buf | Returns an input data buffer to printer system. | Language has "emptied" input data buffer. |
| return_unused_input | Returns a partially full input data buffer to printer system | Language does not want input data, possibly because of job boundary detection. |
| exit_lang | Indicates this language is no longer the interpreter for input data. | Language detects PJL universal exit language, or job_boundary flag set on get_input. |
| feed_media | Requests media be fed. | Imaging is to begin for a new page. |
| media_size | Requests dimensions of a media size. | Language wants to know initial imageable area of media. |
| image | Sends image swaths to the printer system to be printed. | Language has rendered, and is ready to print swaths. |
| send_output | Requests data be sent to the host system | Language wants to send data to host. |
| read_nvram | Reads data from nonvolatile RAM. | Language wants to retrieve data it has stored in nonvolatile RAM. |
| write_nvram | Writes data to nonvolatile RAM. | Language wants to store data into nonvolatile RAM. |
| printer_control | Flexible way to perform printer operations such as I/O reconfiguration and special media control. | Language wants to reset I/O configuration parameters or perform another special printer operation. |
| async_lang_status | Notifies printer system of a change in language status. | Language subsystem has a change in status. |
| restart | Requests restart of the language subsystem. | Language command to restart or catastrophic error occurred. |

Fig. 16. Interface library routines provided by the printer system firmware.

language, PCL 5C or PostScript, the job needs to be sent to. Assuming there is no language initialized, the `lang_init_req` routine, provided by the target language subsystem, is called at a predetermined address.

The `lang_init_req` routine passes the resources the language subsystem will need to operate. The parameters passed to the language on the `lang_init_req` call specify the location of the information window, the RAM available to the language, pointers to operating system routines, a range for process priorities, and pointers to the printer system interface library routines, including the initialization acknowledgment call, `lang_init_rsp`. The language subsystem can call the `read_nvram` and `write_nvram` routines to retrieve or set information in the nonvolatile memory area allocated to the particular language. A call to the `lang_init_rsp` routine, provided by the printer system, indicates the language has finished initializing and is ready to accept a print job. The `lang_init_rsp` routine also passes the addresses of the remaining language subsystem interface library routines. Thus, with the exception of the well-known `lang_init_req` routine, the printer system and language subsystem are linked dynamically at run time.

When a print job is ready to be delivered and the appropriate language is initialized, the `enter_lang` routine is called by the printer system to indicate that the language subsystem is now the parser of the input data stream. The language subsystem uses the `get_input` routine to retrieve input data and the `return_io_buf` and `return_unused_input` routines to return I/O buffers back to the printer system. The language subsystem can become involved in imaging and in other interactions described below while parsing input data. The language subsystem remains the parser of the input data stream until it recognizes a valid exit event. The exit events on the DeskJet 1200C include the printer job language universal exit language sequence, a nonzero job boundary flag as a `get_input` routine parameter, an end-of-job character (control-D) for PostScript, and others. Once an exit event is recognized, the language subsystem calls the `exit_lang` routine to indicate that it no longer wishes to be the interpreter of the input data stream. Status reporting and any imaging that the language is busy doing continue following an `exit_lang` call.

After an `exit_lang` call, the personality manager examines the input data stream to determine where the next job goes. If the job is targeted for a language that is already initialized, the `enter_lang` routine is simply called again. This enables the language subsystem to begin parsing the next job while the previous job may still be printing. If the next job is for a different language than the one initialized, the `lang_die` routine for the initialized language is called. This instructs the language to finish any imaging it may be doing, return all I/O buffers back to the system, delete the processes it spawned, and otherwise prepare to die. Once a language returns from `lang_die`, the printer system is free to initialize a new language subsystem as described above.

In addition to the initialization, personality management, and language parsing side of the interface, the language subsystem is also involved in imaging. The language calls the `feed_media` routine to cause a sheet of media to be fed in preparation for the image to be placed on it. The request is queued by the printer system if it is busy printing a previous page. When the media is actually fed, the printer system calls the acknowledgment routine, `media_fed`. After feeding

the media, the language subsystem renders the image into image buffers that cover a portion of the output page, and calls the image routine to pass the image data to the printer system for printing. The language subsystem need not wait for the `media_fed` routine before making image calls if it wants to work ahead. The `swaths_imaged` call is the printer system's way of acknowledging it has finished processing the image data and the language subsystem is now free to reuse the associated image buffers. An end-of-page parameter on the image routine indicates the printer system should eject the page following the placement of the image data on the media.

When the language is initialized, the printer system and the language subsystem exchange status and event signals through the `async_periph_status` and `async_lang_status` routines. The DeskJet 1200C printer system passes online, door open, jam, and other status, as well as the eject page and manual feed timeout events, to the language subsystem using `async_periph_status`. The DeskJet 1200C language subsystem passes its operating state (idle, busy, waiting) and a job end event using `async_lang_status`. The `printer_control` routine is used in the DeskJet 1200C to change the name and type of the printer as it appears on AppleTalk networks.

Documents

The language interface specification is broken into two documents: a device independent language interface specification and a device-specific document. This is to help facilitate reuse of the language interface. The device independent document provides a generic description of the information window, descriptions of the routines in the interface library, and the detailed model-of-use section, all of which apply to any device using the language interface. The device-specific document adds the level of detail required to specify the use of the language interface on a particular device such as the DeskJet 1200C printer.

For example, the `feed_media` routine, provided by the printer system to cause a sheet of media to be staged for printing, has parameters for specifying the source tray, destination tray, media size, media type, and print quality. The device independent language interface specification describes these parameters in a generic sense, but does not enumerate the valid values for a particular device. The DeskJet 1200C-specific document is the source of information as to what sources, destinations, media sizes, media types, and print quality values are valid for the DeskJet 1200C.

This approach to splitting the language interface specification has been beneficial. The DeskJet 1200C printer is the second of three devices to use this language interface so far. The HP PaintJet XL300 printer was the first, and the recently introduced HP DesignJet 650C large-format plotter also uses the language interface with the PostScript language (the DesignJet 650C does not support PCL 5C). The DeskJet 1200C and DesignJet 650C are able to reuse the device independent language interface developed for the PaintJet XL300 with only three minor enhancements. The DeskJet 1200C device-specific document was highly leveraged from the PaintJet XL300's with changes that reflect differences in the addresses for the `lang_init_req` routine, in the supported media sizes, in the front panels, and in other minor areas. The language interface is currently being considered for use in other products under development at various HP divisions.

Since the language interface supports two different language developers, it has to be simple, effective, efficient, and flexible. The simple view of a language subsystem that is the language interface fits the model of both PCL 5C and PostScript well. It is simple, and yet it is full-featured, supporting the best that PCL and PostScript have to offer. Because the language interface was designed with the complete firmware architecture in mind, it is efficient in both I/O access and imaging access. The split between a device independent document and a device-specific document strikes a balance between facilitating modularity and reuse and providing a realistic, flexible framework for implementation on a device.

Ever since version 1.0 of the language interface specification was released in May 1991, midway through the development of the PaintJet XL300 printer, modifications to the language interface have been through a formal change process. The change process provides a way to develop consensus and enhance the language interface in a controlled manner. Working with the PCL 5C development team and the PostScript team at Adobe Systems, the HP language interface team refined the interface using the change process. As each issue presented itself, the engineers involved would address the issue with a language interface change solution. A preliminary consensus would be reached, and a formal change would be submitted on an electronic bulletin board. After a review time, during which the change could undergo further review and revision, the change would be closed and incorporated into the implementation. The language interface specification, and perhaps more important, the language interface implementation, required constant communication with both groups of language developers. The DeskJet 1200C development team used the change process for both device independent document changes and device-specific document changes. The change process remains in place today to accommodate the needs of new products in development.

Screen Calibrator

With the advent of color output devices, many users have been disappointed with the consistency of the colors that their peripherals produce. Their carefully crafted screen image or scanned photograph is unacceptably distorted by many printers.

But how does one go about giving users the “no surprise” color that they need? The HP DeskJet 1200C printer achieves this by allowing the user to help characterize the particular CRT and display card. Armed with this knowledge, the DeskJet 1200C printer driver for Microsoft Windows can better match a user’s output with what appeared on the screen.

Consider two RGB triplets: 128,0,0 and 180,0,0. Other than saying that the latter is “redder” than the former to some unknown degree, those numbers alone convey very little information. When these RGB values are passed to various printers on the market today, one quickly discovers that their meaning is quite arbitrary; the actual colors output by different printers are surprisingly different.

The RGB triplets used by Microsoft Windows are not rigidly defined. Standards exist for specifying particular colors (these standards are often referred to as color spaces), but

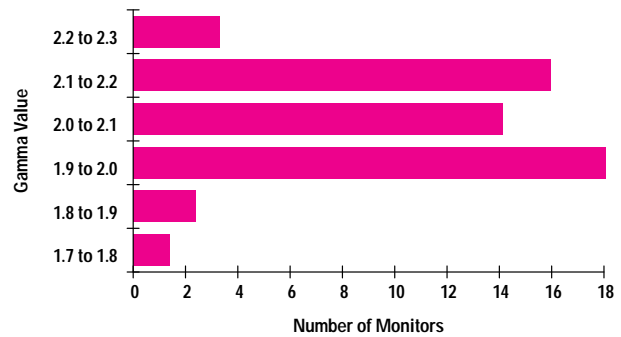


Fig. 17. Gamma values of identical monitors were found to vary considerably.

RGB values in most operating systems today are not specified in a standard color space.

Returning to the problem at hand, the situation is even worse than it seems at first glance. Not only does every printer interpret RGB values differently, but so does every display card and every monitor. To top it all off, significant variations can be seen even among samples from the same brand and model of display equipment.

To get some idea of how significant these differences were, consider the case of several HP D1182 monitors that were tested in-house. Driven by a variety of different display cards, the monitors had gamma values (which will be explained later) that ranged from 1.7 to 2.3 (see Fig. 17). In general, a gamma difference of 0.1 was found to be noticeable. Overall variations (various monitors and display cards) were even more significant.

From this information, it was decided that no output matching technique could simply ignore these variations and still produce accurate hard-copy reproductions of CRT displayed data. Fortunately, HP Laboratories had already done some pioneering work in the field of CRT characterization.

If one can characterize a display system sufficiently, then it is possible to predict (in a standard color space) what the RGB triplet 128,0,0 actually means. By characterizing a color printer such that printer RGB triplets can be obtained to reproduce a standard color space value, one can then, in theory, accurately reproduce the color the user sees on the CRT on the output device.

The HP DeskJet 1200C, like all HP inkjet printers, shows relatively little color variation from one sample to the next. It can therefore be characterized statically with virtually no impact on the matching solution. There is, however, another problem that must be dealt with.

As one might imagine, different output technologies have different ranges of reproducible color. By way of illustration, if the RGB triplet 0,0,255 is specified on the screen, it will most likely produce a blue that the printer is unable to match. Conversely, when a DeskJet 1200C printer is given the triplet 255,255,0, it produces a yellow color that few CRTs can match.

The total collection of colors that a device can produce is referred to as the device’s gamut. Gamut mismatch is the problem described in the previous paragraph. Since we are using the display system as a reference point for the printer,

the colors that the printer can produce but the CRT cannot produce are of no real concern.

The other part of the mismatch, CRT colors that the printer cannot accurately reproduce, is handled in the printer characterization. Since the printer characterization is done in a standard color space, information about nonreproducible colors can be imbedded in that characterization. Out-of-gamut colors are translated to colors the printer can produce in a process known as gamut scaling.

All decisions about the printer are made before the color matching software is ever put on the distribution disk. Characterizing a particular CRT, however, is another matter entirely. To match a CRT accurately, the DeskJet 1200C driver uses an HP-developed *screen calibrator tool* to obtain the information it needs about the display system of the user.

The introductory screen of the screen calibrator gives the user three options. The Standard Screen option gives default values for all the measurements the screen calibrator makes (loosely based on a Sony Trinitron display). Two calibration options—*precise* and *most precise*—give the user either a set of color screens or two black and white screens. The choice between the calibration options is a simple trade-off between ease of use and accuracy.

To better explain the measurements the screen calibrator makes, it is helpful to review how a CRT works. A CRT makes images by hitting phosphors with electron beams. In a color CRT, three different colors of phosphors (red, green, and blue) are struck by three electron beams. As more energy is applied to a patch, it glows brighter. From a distance, the colors of the three patches blend together to produce the varying hues the CRT can display.

Now imagine sending a series of colors to the CRT, beginning with 0,0,0 and running to 255,0,0. This series of reds will not, on virtually all display systems, produce 256 patches with equal-intensity steps between them. Furthermore, some values close to black, such as 5,0,0, often cause no noticeable activation of the phosphors. This threshold of activation, or deadband area, has been dubbed the *dc offset* of the display system.

The color intensities produced after passing the activation threshold follow an exponential curve:

$$I_A = I_I^\gamma$$

where I_A is the actual output intensity and I_I is the intensity level desired. The intensities are normalized and have values between 0 and 1. The exponent of this curve, known as gamma, is the important piece of data to derive. Using the screen calibrator, users perform tests that determine the dc offset and gamma of a display system.

Figs. 18 and 19 show how the screen calibrator interacts with the user to determine the gamma and dc offset. In Fig. 18, the user moves the slider until the center of the rectangle can just be distinguished from the completely black sides. This allows the screen calibrator to measure the dc offset of the display system.

The gamma determination is considerably more challenging to the user. By alternating colored and black lines on the

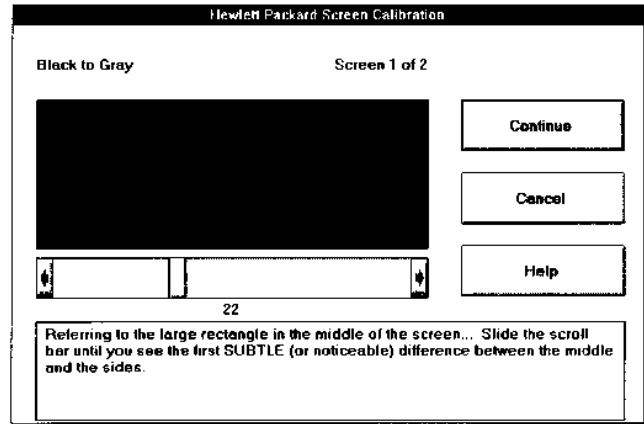


Fig. 18. The screen calibrator tool lets the user help match the DeskJet 1200C printed output to the monitor screen. This screen is for determination of the monitor's dc offset.

sides of the central patch, different intensities can be accurately created (see Fig. 19). The problem is that the user must somehow coerce the alternating lines into a solid patch of color. This can be accomplished by the sophisticated visual process of squinting, as suggested by the instructions, but moving away from the screen or removing one's eyeglasses can sometimes serve the same purpose.

Having successfully squinted and adjusted, the user has made the center patch match the wide patches and the whole rectangle appears to be of one intensity. This allows the screen calibrator to correlate the actual intensity—the bars—with the value that the display card and monitor need to display that intensity. A curve is then fit to the points to derive gamma.

The difference between the precise and most precise calibrations is twofold. First, the most precise calibration determines the gamma of the red, green, and blue channels of the system separately, while the precise calibration uses white, effectively using the user's eye to average the three channels.

The second difference between the calibration options allows adjustments for the kind of light that illuminates the printed output. The user's DeskJet 1200C prints a purple-colored

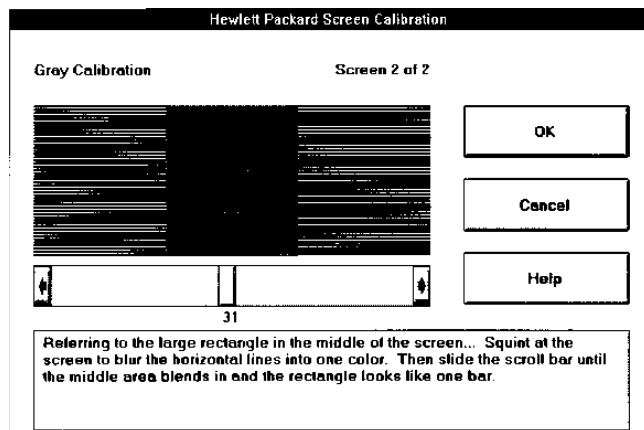


Fig. 19. Screen calibrator tool screen for determination of the gamma of the monitor.

patch, which the user then compares to a series of patches on the screen. Depending on the kind of lighting around the system, the user will see the printed patch as either more bluish or more purplish than the displayed patches. The user selects the displayed patch that most closely matches the printed patch.

Once all this interactive information is gathered, color maps are generated for each combination of dithering and media type. This is necessary because each of these combinations has a different effect on the colors produced by the printer.

Two main classes of color maps are generated. Match to Screen maps faithfully represent on paper what appears on the user's screen. More Vivid maps increase the color saturation of the output.

Thus, by interacting with users to determine the characteristics of their specific display systems, the screen calibrator tool of the DeskJet 1200C Windows driver helps deliver the accuracy and consistency that users demand.

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Reference

1. *Tile Vector to Raster Conversion Method*, U.S. Patent #5,028,848, July 2, 1991.

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