

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.

Robert Giles
Development Engineer
San Diego Printer Division

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

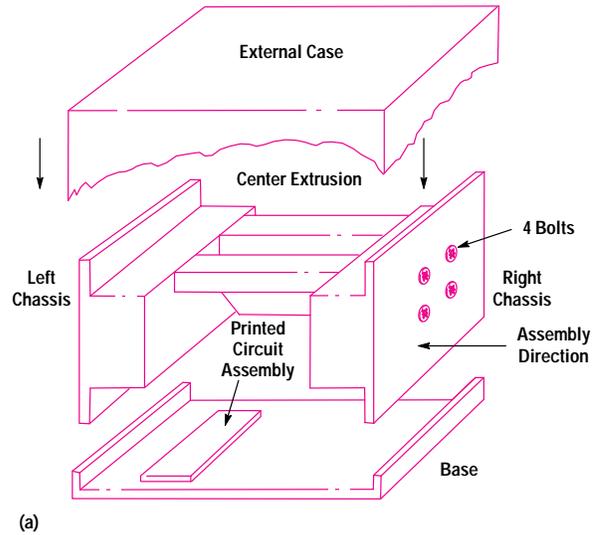
The HP DeskJet 1200C printer project inherited a large body of work, both theoretical and physical, from an earlier project, which developed a low-cost color printer for the office using two print cartridges (black and tricolor). Work on that printer determined a basic media path and a set of features 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.

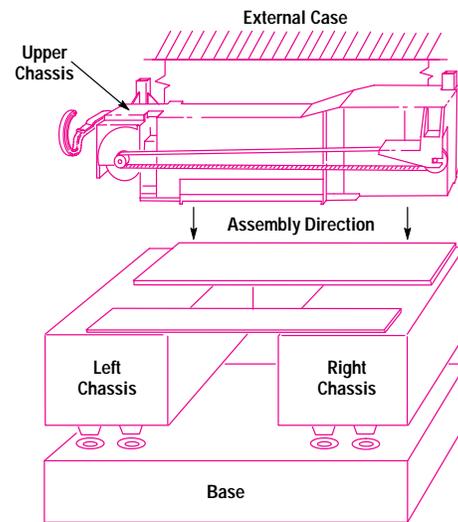
Early in the investigation phase of the project, perhaps because of the head start provided by the earlier project, a prototype of the new printer was built that represented most of the functionality of the final product. This prototype gave the project a physical reality and greater stability in the 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.



(a)



(b)

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.

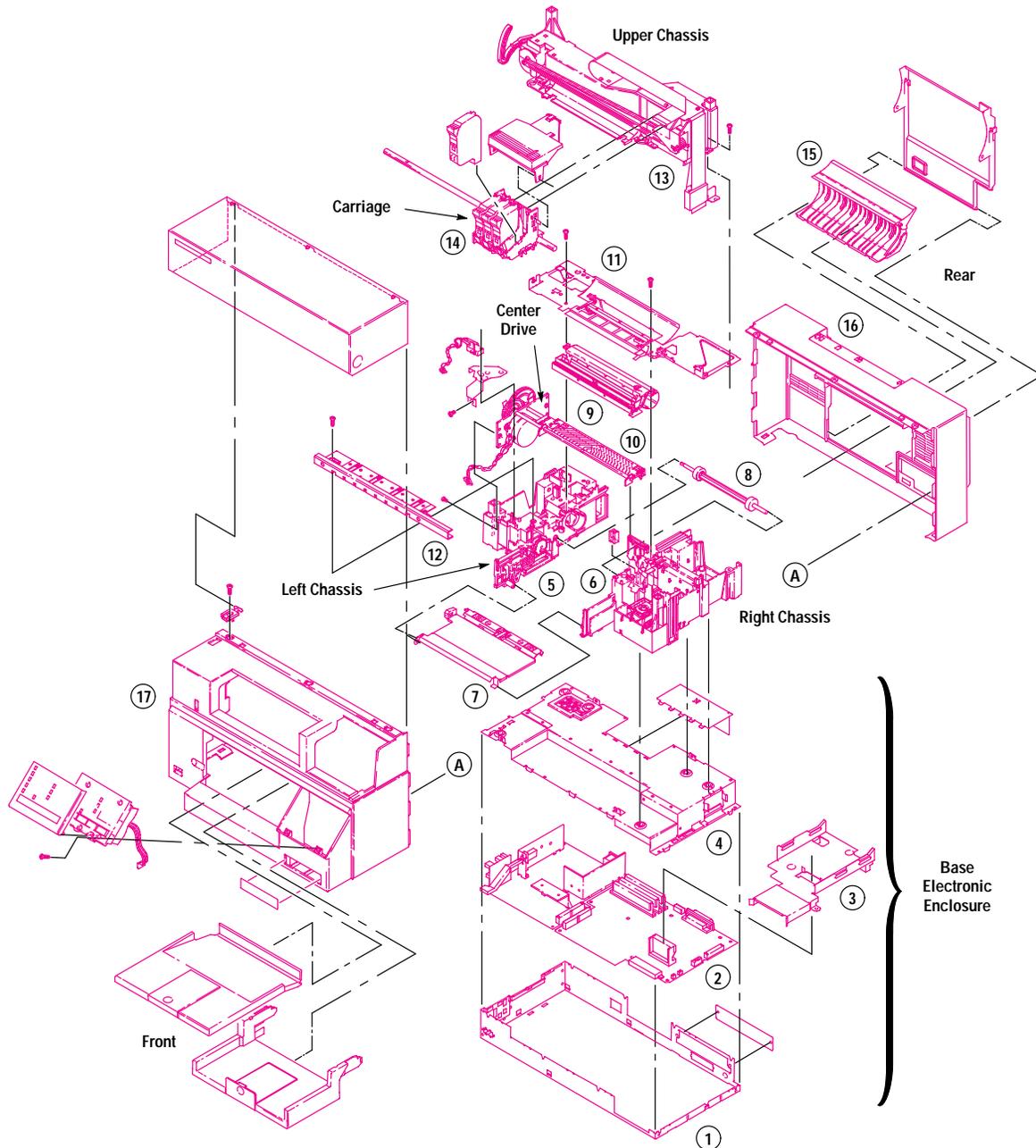


Fig. 2. Exploded view of the HP DeskJet 1200C printer showing the functional areas of the mechanical system. Major mechanical architectural subsystems include the chassis, the base, and the case assemblies. Assembly is modular and “top-down.” The top level assembly sequence is numbered.

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.

Donald Clugston
Packaging Engineer
San Diego Printer Division

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

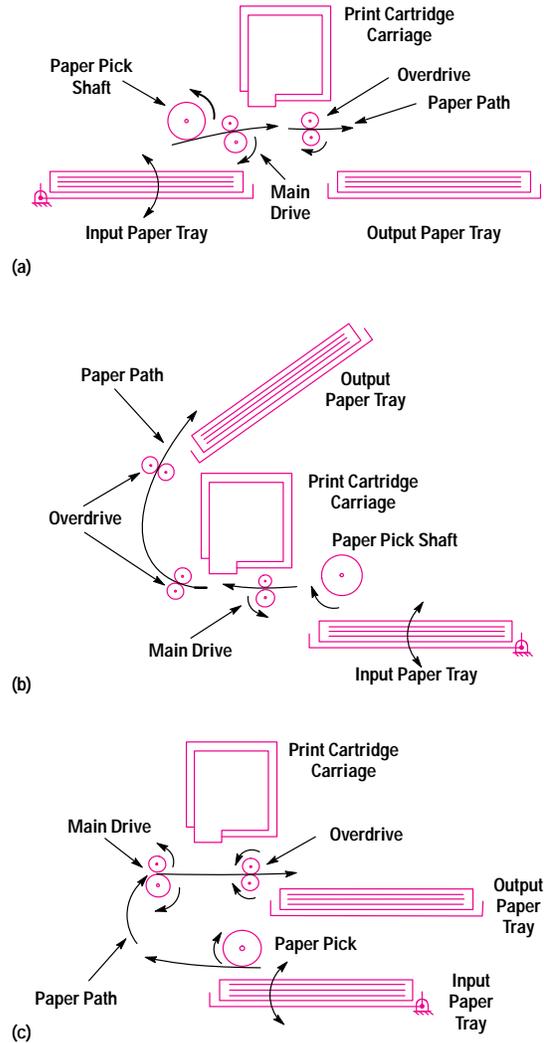


Fig. 3. Media path alternatives and basic product architectures. In the simplest architecture (a) the media path is flat. No bending of the media makes it easier to print on specialty stock such as envelopes. The biggest advantage is speed because the media path is short. However, the footprint is large. 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.

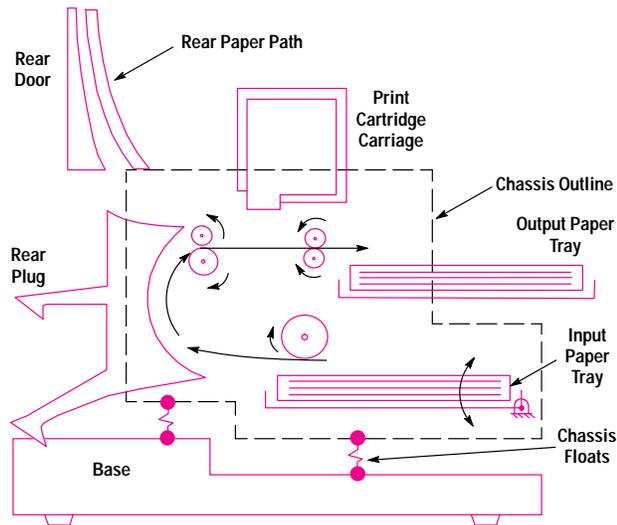


Fig. 4. The dual media path of the DeskJet 1200C printer is an enhanced version of Fig. 3c. It has a small footprint and low cost. Speed is not optimized but is acceptable. A rear media path that doesn't bend the media so much is added for specialty items such as envelopes, cards, and labels. The media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

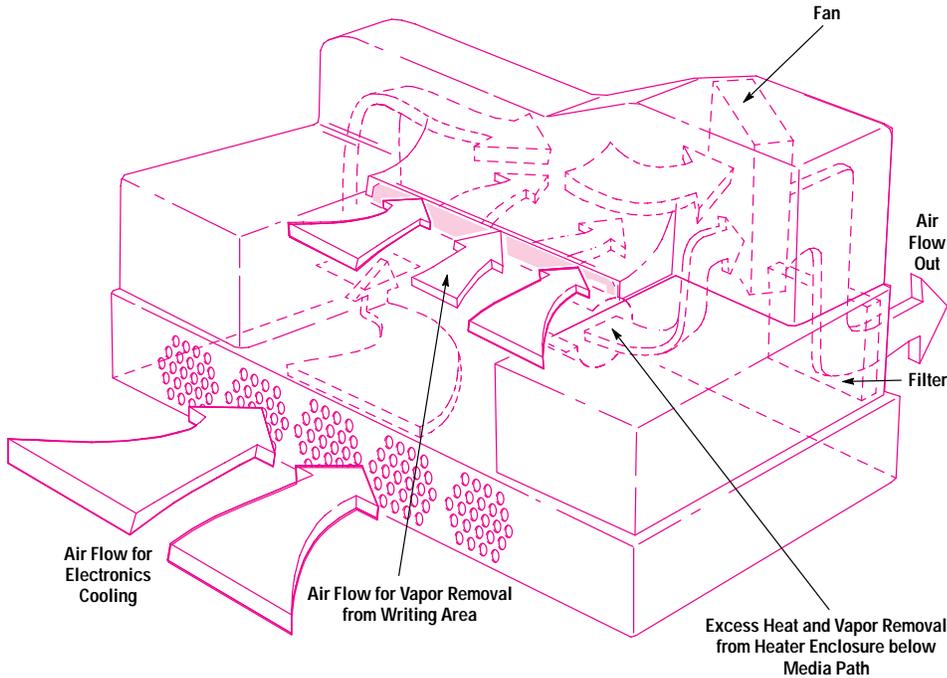


Fig. 5. Airflow paths through the DeskJet 1200C printer.

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,

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

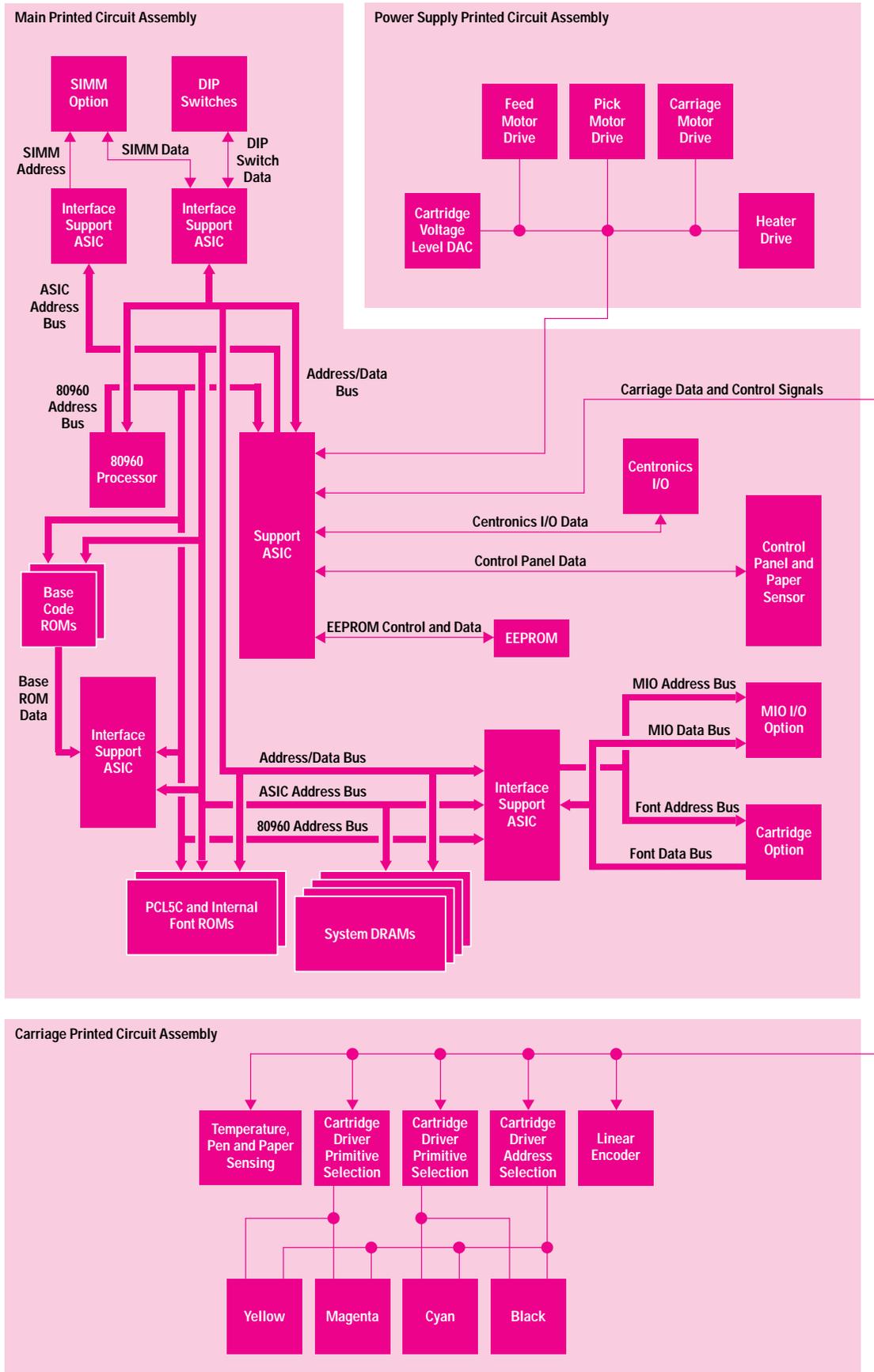


Fig. 6. Simplified electrical system block diagram of the DeskJet 1200C printer.

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

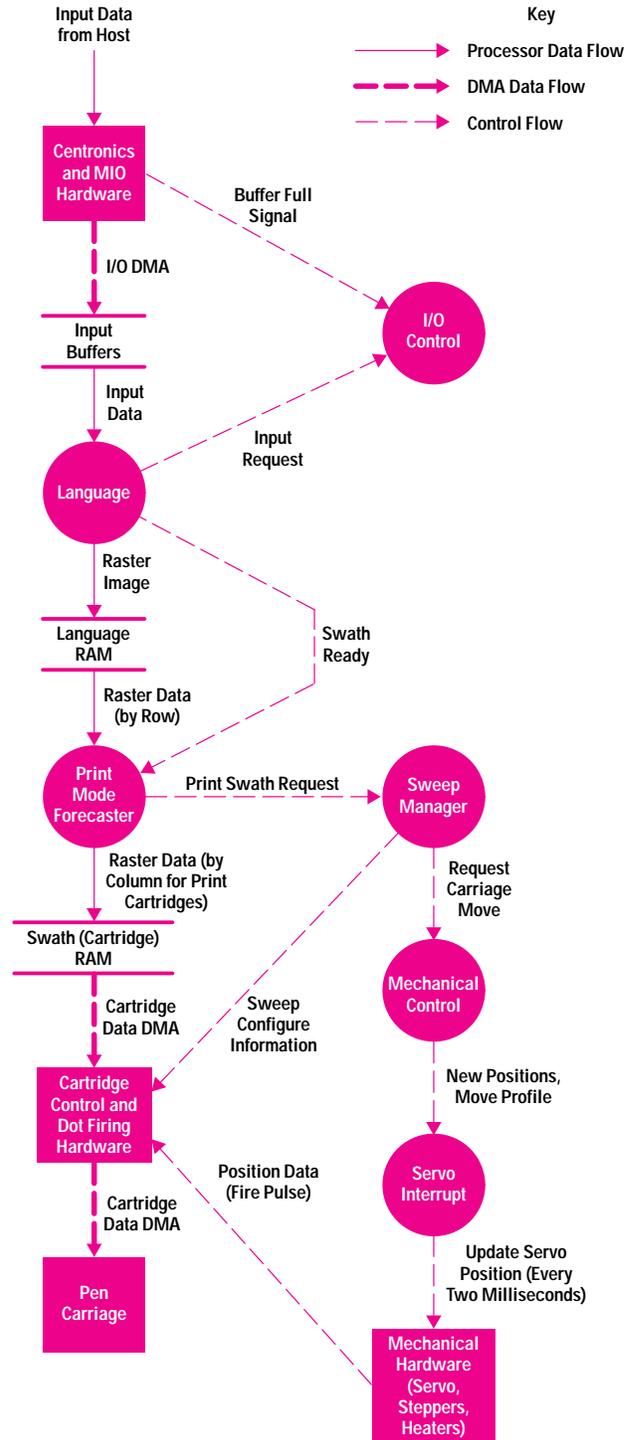


Fig. 7. DeskJet 1200C firmware overview.

- 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.