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Development of a Low-Cost, High-Quality Graphics Plotter

A novel plotting technology and a design for low manufacturing cost have resulted in an inexpensive X-Y plotter capable of fast, high-resolution, graphics output.

by Majid Azmoon

HEWLETT-PACKARD'S San Diego Division has been supplying high-quality graphics plotters to operate with HP computers and measurement systems since the development of the 9125A Plotter over a decade ago. During this time, several trends have developed. The plotter market is composed of several segments that are changing. Within computer graphics, the personal computer revolution is taking place. More and more low-cost personal computers are becoming available with capabilities previously reserved for much larger and more expensive systems. Examples of low-cost, high-performance HP personal computers are the HP-85, and more recently, the HP-87XM and HP-86. As computation prices come down, the need for low-cost, hard-copy graphics increases.

At the same time, many measurement devices are becoming available that directly use graphics plotters, providing an attractive, cost-effective alternative to photographing CRT displays and plotting data by hand. Many HP measurement devices such as the 4145A Semiconductor Parameter Analyzer[1] directly support plotter graphics, and many more supply data to a controlling computer, which in turn can drive a graphics plotter.

These two trends, the availability of personal computers with big-computer capabilities and intelligent instruments supporting plotter graphics, have precipitated the need for a low-cost plotter designed without sacrificing any of the high quality HP customers have come to expect. To meet this need, HP has developed the 7470A Graphics Plotter (Fig. 1) with the following features:

- Accommodates either 8½-by-11-inch (ANSI A) or 210-by-297-mm (ISO A4) paper or HP's overhead transparency film.
- Two built-in pen stalls make two-color plotting easy. For additional colors, the plotting can be halted from the 7470A's front panel or by program control, new pens can be installed, and the plotting resumed.

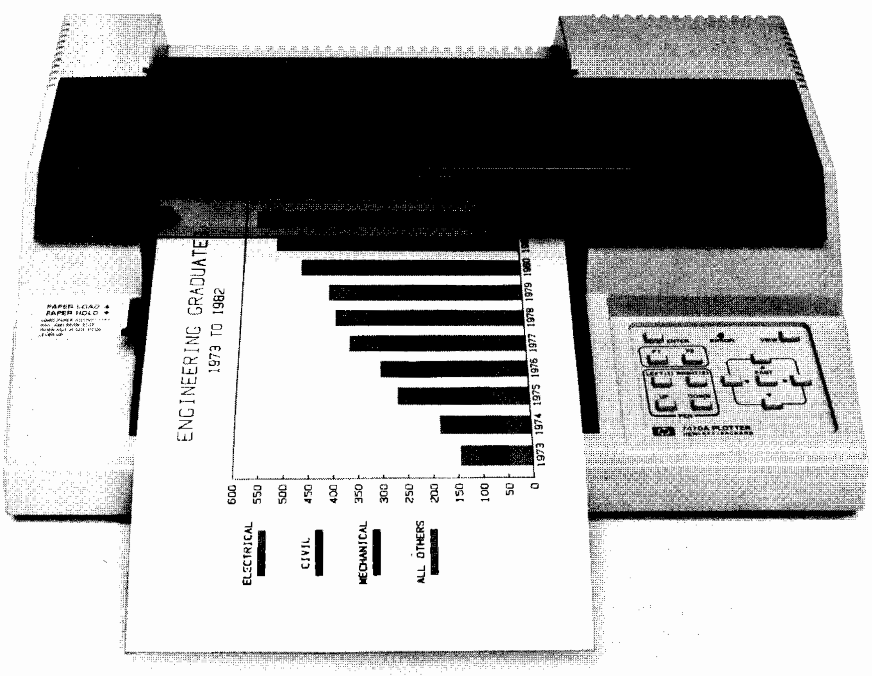

Fig. 1. *The HP 7470A Graphics Plotter is an inexpensive instrument that provides high-quality hard-copy graphics output for small computer and smart instrument users. High-resolution multicolor plotting, five internal character fonts, and the use of standard notebook-sized paper or overhead transparency film are some of the features of this low-cost machine.*

Manufacturing Team in the R&D Lab

A manufacturing team was formed early in the lab prototype phase of the 7470A Graphics Plotter project and became an integral part of the development effort. Its primary responsibility was to influence the product design for improved manufacturability. This team developed the processes, machines, tooling, and test fixtures for the fabrication, assembly and testing of the 7470A.

Objectives

The manufacturing team established a set of eleven objectives. The primary objective coincided with that of the development team, which was to keep the total manufacturing cost of the plotter below an established goal. The plotter was not only to be low in cost, but the volume was projected to be over two times that previously experienced by HP's San Diego Division. This meant things had to be done differently on the production line.

The manufacturing team chose to try to provide a printed circuit board without gold, a cost-effective alternative to silk screening, and an automated assembly line that would fit into 2700 square feet of factory space. Two other major goals were to ensure a greater than 50% yield of good loaded printed circuit boards at the first pass on an HP 3060A Circuit Test System and better than 97.5%-good printed circuit assemblies arriving at the assembly line. The team was able to meet the total manufacturing cost target value within 10% and met all of the other objectives, with the exception that gold is needed under the dome switches in the 7470A's keyboard area.

Parts Minimization

The basic approach used throughout the product's development to meet the manufacturing objectives was to reduce the number of parts to a minimum. The product was split into modular subassemblies to simplify and reduce labor. This breakdown of the product into major modules such as the motor encoder assembly, power module assembly, mechanics, and printed circuit board made it easy to assign to each of the manufacturing engineers one part of the product to improve. As mentioned on page 15, machined parts, painted or finished parts, interconnect cables, assembly line adjustments, and a cooling fan were considered undesirable. Although total success was not realized in avoiding all of these, their use is only about 25% of what it might have been.

Molded Parts

The manufacturing team realized that, because the product had many molded parts, extensive testing with actual molded parts would be essential. Many of the critical molded parts were tooled with temporary molds before strife and reliability testing to allow test results to be meaningful. The most critical of the temporary molded parts was the heart of the plotter, the chassis. This major structural part holds the dc drive motors, shafts, extrusion, and idler, and acts as the writing surface for the paper. The large temporary mold for the chassis went together like a three-dimensional jigsaw puzzle. There was some uncertainty about molding such a large part and still being able to maintain the critical dimensions. However, the first prototype mold yielded a successful part. Having these molds also allowed making more prototype plotters to test at a reasonable cost.

Assembly Line

To meet the automatic assembly line objective, four alternatives were proposed. Two of the proposals included the use of carousels and two included transporters. The assembly line approach chosen was to achieve the following:

- Reduce the labor to build the plotter by having the assemblers spend more time assembling and less time moving parts.
- Reduce the amount of space required to assemble the projected high volume.
- Let the assemblers work at their own pace while providing a serious production atmosphere.

An economic study was made and then an assembly line that uses one progressive assembly carousel, flow racks, roller interchange, and a burn-in carousel was ordered. With this assembly line the above objectives were achieved.

Acknowledgments

We are deeply indebted to Terry Siden for his guidance and encouragement. Manufacturing team members were Gary McLeod, Bob Ferrari, John Powell, Steve Sakumoto, Wally Halliday, John Morton, Bill Gunther, Carol Kinslow, Gale Moreland, and Walt Borra. A great deal of thanks is owed to Ron Vanderlugt and his coworkers in the mold shop. The San Diego Division's model shop under Richard Berktold and tool room under Norm Ashley came through every time. The electronic tooling department under Bud White and mechanical tooling department under Gary McLeod got us what we had to have to succeed.

-Bob Porcelli

- Five internal character sets: English, Math, French and German, Scandinavin, and Spanish. Text can be written in any direction, with or without character slant, and in many sizes.
- Seven built-in dashed line fonts and symbol plotting capability make it easy to design understandable graphs.
- Forty-two built-in HP-GL (Hewlett-Packard Graphics Language) commands. HP-GL software written for other HP plotters can be easily adapted to the 7470A.
- Addressable step size can be as small as 0.025 mm. Repeatability to a specified location is 0.1 mm with any given pen, and 0.2 mm from pen to pen.
- Pen acceleration is approximately 2g and plotting speed is programmable in 1-cm/s increments from 1 to 38 cm/s. Labels and annotations can be drawn at speeds up to 5 characters per second.
- Three interface options are available—HP-IB,* RS-232-C/CCITT V.24, and HP-IL (Hewlett-Packard Interface Loop. See article on page 16).
- No periodic readjustments are required to maintain plot quality.
- Maximum power consumption is only 25 watts.

Providing these features was a considerable challenge to the 7470A design team.

Low-Cost Design Approach

Low manufacturing cost, high quality, performance and reliability were the primary project objectives. To achieve these objectives, a technology had to be chosen. Microgrip

*Hewlett-Packard Interface Bus, HP's implementation of IEEE Standard 488 (1978).

drive technology, invented in HP Laboratories[2] and proven in the 7580A Drafting Plotter[3] and the 4700A Page Writer Cardiograph,[4] eliminates the problems associated with conventional plotters by doing without heavy moving arms, paper transport drums, and belts. Consequently, because the microgrip drive system offers mechanical simplicity and low mass, less power is required to drive the pen and media. This simple mechanism leads to a dynamic system that is easy to control, aiding the design of a better servomechanism to give the plotter higher performance and output quality. Although step motors would have furnished a lower-cost X-Y drive, dc motors were chosen to provide much higher plotting throughput. An optical encoder built into each dc motor provides the necessary feed-

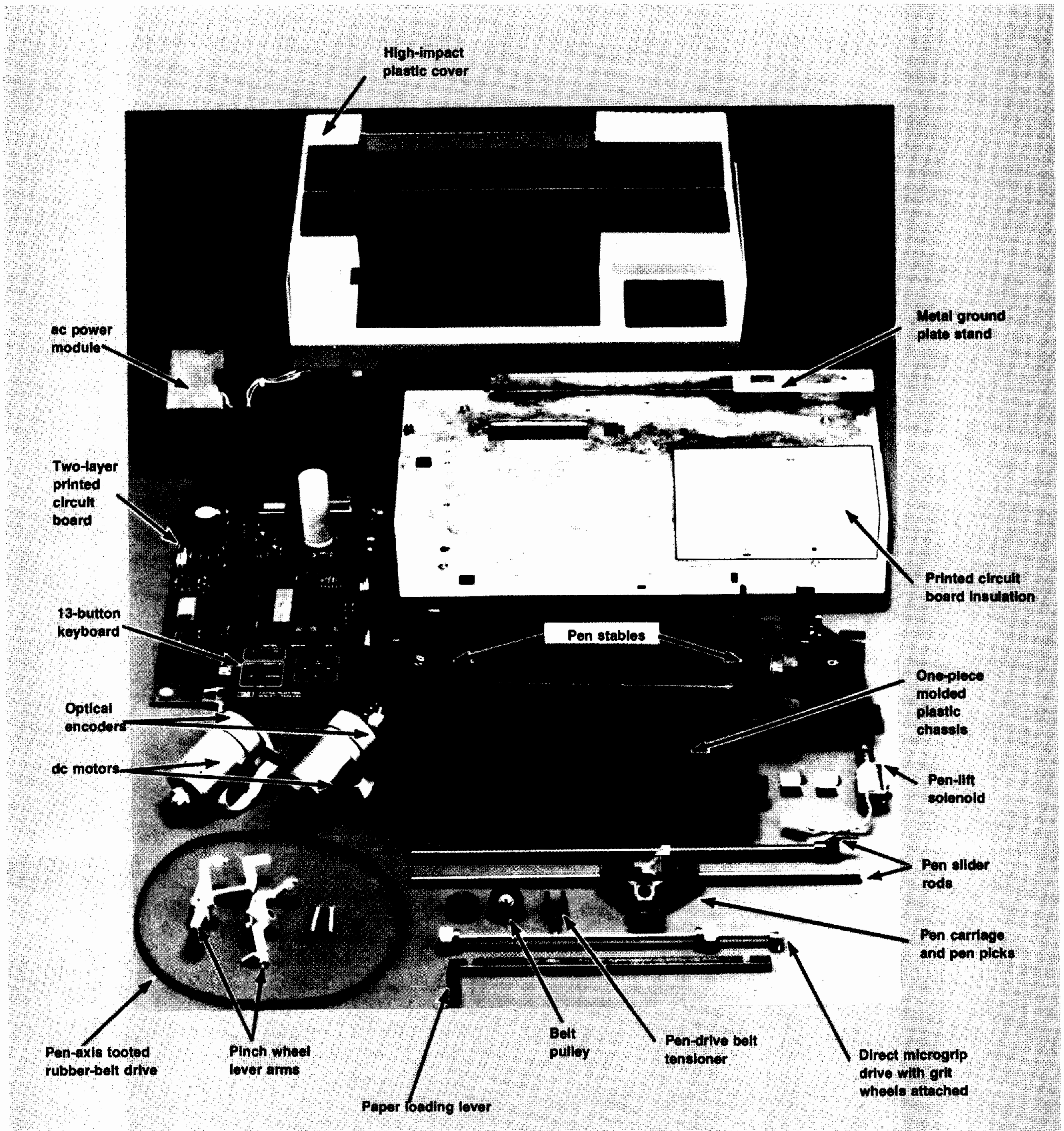

Fig. 2. *Exploded parts layout for 7470A. The low manufacturing cost and high product reliability are made possible by a simple design requiring less than 200 parts, approximately half of which are contained on a single printed circuit board.*

back to control the X-Y movements. This optical encoder was specially designed (see article on page 26) to meet the low-cost objectives for the product.

After the technology was chosen, other low-cost design strategies had to be developed (see article on page 23). They were as follows:

- The plotter design was broken down into several modular assemblies such as the motor and encoder, power supply, electronics, mechanics, and packaging. Cost objectives (both materials and labor costs) were set for each module.
- Low-cost manufacturing processes were selected wherever possible, such as:
  1. Custom integrated circuits—HP-manufactured NMOS servo chips[5]
  2. Semicustom integrated circuits to perform a number of logical functions
  3. Two-layer printed circuit board
  4. Injection-molded plastic parts
  5. Linear logic power supply (unregulated supply for motor drivers)
  6. Low parts count (see Fig. 2).
- Avoiding the use of conventional, expensive manufacturing and design techniques as much as possible. For example, eliminating or reducing the use of:
  1. A cooling fan
  2. Optical sensors and microswitches
  3. Adjustments
  4. Painting for mechanical parts
  5. Silk screening
  6. Multiple printed circuit boards and the associated number of expensive, less-reliable interboard connectors.
- Contracting with several specialized companies to manufacture some standard parts and partial assemblies, such as the selectively gold-plated printed circuit board and the power module wire assembly. These specialized vendors offer high-quality parts and a low-cost alternative to manufacturing these parts in-house.

Reliability

Low maintenance cost is essential for a low-cost device. This objective should be achieved with high product reliability. Most of the low-cost approaches listed above substantially increased the reliability of the plotter as well.

Extensive thermal modeling and mapping were conducted in the early phases of the design to ensure that heat dissipated inside the package would not significantly affect the reliability of the components. Several strife tests were performed to improve the plotter's reliability. A strife test involves operating many units at maximum performance while the units are undergoing extreme temperature cycling. The temperature was cycled between −5°C and 60°C, with each full cycle taking eight hours. As a result of these tests, many design weaknesses were discovered and subsequently corrected.

Acknowledgments

The success of the 7470A is a tribute to the excellence of the design team and manfacturing support group. The author would like to thank Norm Johnson for his leadership, Myron Hunt and Bryan Butler for their product marketing contributions, and Dave Leong and Lynn Palmer for their product design efforts. Special thanks go to the R&D lab and the IC group at HP's Corvallis Division and to HP Laboratories.

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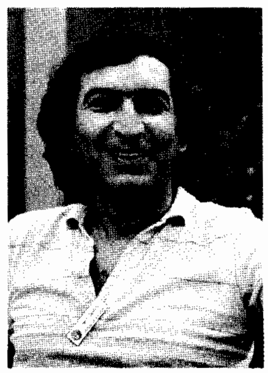

Majid Azmoon

Maj Azmoon joined HP in 1973 and worked on the 9872/7221 Graphics Plotters and 7245A Plotter/Printer before becoming the R&D project manager for the 7470A. His work has resulted in two previous HP Journal articles and two patents related to the 7245A. Maj was born in Tehran, Iran and holds a BSME degree from California Polytechnic University (1969) and the MSME degree from the University of Southern California (1971). He is married, has a son, and lives in Poway, California. His outside interests include playing racquetball, piano, and electronic music synthesizer, and restoring old Ford Mustang automobiles.

CORRECTION

In our November 1982 issue, Fig. 13 on page 26 had some incorrect labels. The horizontal axes of the two time window plots on the left side of that figure should be labeled **t**, not **f**. On both sides of that figure, $m\Delta t$ should be $M\Delta t$.

Controlling a Graphics Plotter with a Handheld Programmable Calculator

by Robert M. Miller and Randy A. Coverstone

THE ADVENT OF THE HP-IL (Hewlett-Packard Interface Loop)* transformed the HP-41C from a programmable calculator into a true computer system with mass memory, a variety of printers, and a video display. However, one capability still lacking was some form of graphics output. The HP 7470A Graphics Plotter with an HP-IL interface and the HP 82184A Plotter Module (Fig. 1) was developed to satisfy that need.

As a computer, the HP-41C possesses a powerful and flexible instruction set, but is limited in speed and memory. While it is possible to connect and control a plotter using only the control functions built into the interface module, the resulting graphics programs would consume most of the available RAM and execution would be painfully slow. The 82184A Plotter Module was designed to free the user from these limitations. By providing a high-level set of graphic commands in external ROM, the HP-41C's system RAM is entirely available for the user's application programs. Further, all of the graphics primitives are written in machine language to minimize execution time.

The HP-41C with the 82184A Plotter Module, the 82160A HP-IL module, and the 7470A Graphics Plotter make up a low-cost, yet powerful graphics solution. The Plotter Module allows HP-41C users to produce bar and line charts as well as function and point plots on paper and transparencies. It also provides the capability to produce bar code of HP-41C programs and data on either the 7470A or the HP 82162A Thermal Printer. The bar code can then be read back into the HP-41C via the HP 83153A Optical Wand.[3]

*HP-IL is an interface system for low-power, portable systems introduced late in 1981. HP-IL will be discussed in next month's issue. Also see references 1 and 2.

Command Set

The 82184A Plotter Module is an 8K-word unit (word length is 10 bits) which adds 52 microcoded commands to the HP-41C's function set, along with a sophisticated interactive plotting program written in RPN (reverse Polish notation). Many of the command names and functions are based on the graphic command sets of the HP 9845 Computer and the HP-85 Personal Computer. This allows users familiar with these products to master the plotter module's commands quickly.

The module's functions are divided into three categories:

- Plotting primitives. These commands set up the plotter, scale the plotting area to any convenient user units, provide windowing, move the pen from one location to another, change pens, raise and lower the pen, draw and

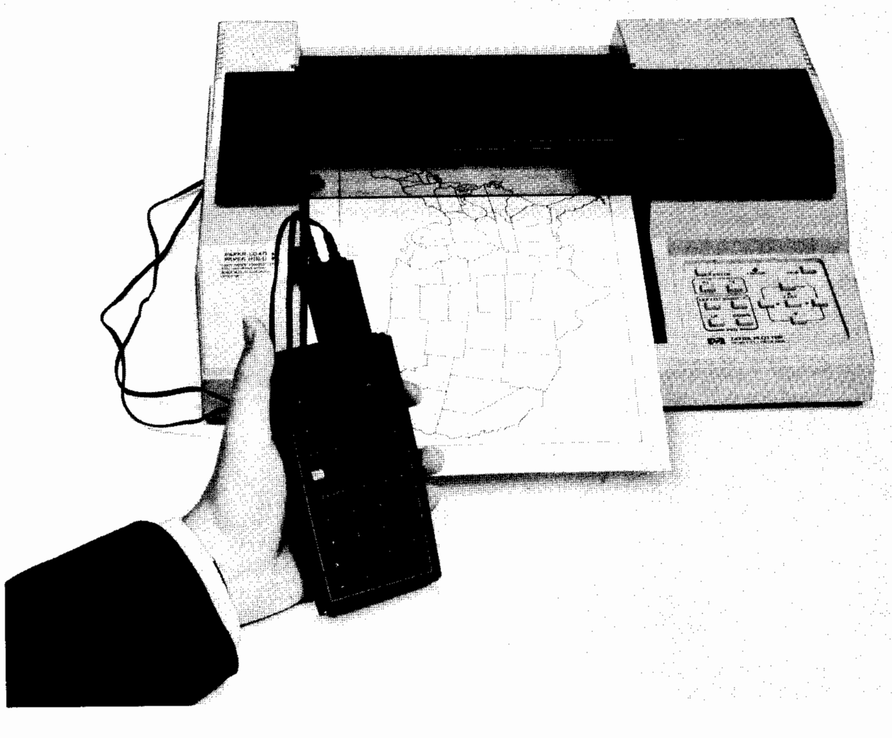

Fig. 1. *The HP 82184A Plotter Module and HP 82160A HP-IL Module are easily inserted into two of the four I/O ports at the top of the HP-41C Programmable Calculator, providing low-cost graphic output to an HP 7470A Graphics Plotter.*

label axes, and digitize points.
- Bar-code primitives. This category contains commands that create the bar-code bit patterns for user programs and data (numeric, sequential, alpha, and alpha append), as well as commands to plot bar code.
- Interactive plotting program. This program prompts the user for the necessary data and then creates a complete plot. It has a wide range of options and is easily extended by user-contributed subroutines. The program provides data to three subroutines that initialize the plotting area, plot the function or data, and annotate the plot. These three subroutines are also available for use in other user programs.

Plotting on the 7470A

Like other HP plotters, the 7470A's platen is divided into addressable units, called absolute plotter units (APUs). On the 7470A there are 40 APUs to a millimeter. To move the pen to a new location on the platen, a plot command is sent to the plotter followed by X and Y coordinates in APUs. However, for the vast majority of plotting uses, these default units are inappropriate. Therefore it is useful to be able to superimpose another scale on top of the APUs.

Executing the plotter module's PINIT command maps a default scale, called the graphic units (GU) scale, onto the area specified by the plotter's lower left and upper right reference points (P1 and P2, respectively). On the 7470A the GU scale provides 0 to 100 units in the Y direction and 0 to 138.9 units in the X direction, using the default settings of P1 and P2.

In addition to scaling the entire platen, it is convenient to be able to specify a portion of the platen as the active plotting area and then superimpose a new scale on this area. Then, after a function has been plotted (Fig. 2), annotation can be done outside of this area so as not to obscure the data. The plotter module's LOCATE statement allows the user to specify any desired subset of the plotter limits, and the SCALE command maps any desired user units (UU) to the plotting area.

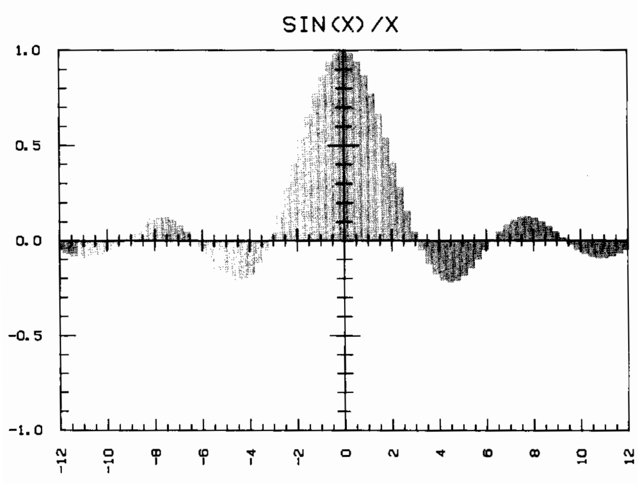

Fig. 2. *Example of a function plotted by an HP-41C, 82184A Plotter Module, 82160A HP-IL Module, and a 7470A Graphics Plotter.*

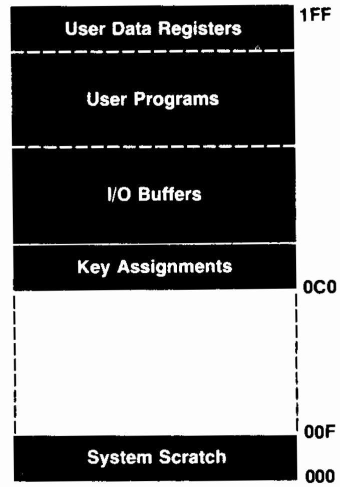

Fig. 3. *Memory map of HP-41C system RAM.*

I/O Buffer

To perform these functions, the plotter module must keep all scale factors, as well as P1, P2, and the endpoints of the area specified by LOCATE in memory. Additional space is needed for status information and temporary storage of bar-code geometry parameters. The module stores all of this information in an I/O buffer.

I/O buffers are created in the HP-41C's memory above any key assignments (see Fig. 3). For the plotter module, a 26-register I/O buffer is needed. The I/O buffer has a header register which tells the operating system and any module scanning memory that an I/O buffer has been found, to which module the buffer belongs, and how many registers there are in the buffer. The drawback to using the I/O buffer structure is that its location in the HP-41C's memory is not fixed. It may be shifted up or down depending on the number of key assignments and the presence or absence of other I/O buffers. Thus, each command must do a memory search to find the I/O buffer before the data it holds can be used. The advantages of the I/O buffer are that data is protected from inadvertent modification, and that its use is totally transparent to the user.

Creating Bar Code

The HP-41C uses a two-level bar code,[4] meaning it is composed of two different bar widths. Narrow bars represent 0 and wide bars represent 1. Spaces between bars serve only as delimiters and carry no information.

Two powerful user-language programs are provided in the plotter module's manual to facilitate producing bar code. The first is a collection of subroutines that labels and plots one row of program or data bar code. The second, PLOTBC, is interactive and provides a quick and easy method for the novice user to produce bar code of programs and data. An example of the output of this program appears in Fig. 4.

Developing a set of plotting parameters that would produce bar code of optimal geometry proved to be challenging. Variations between pens and within the lifetime of a pen result in slightly different ink flow rates and line widths. This difference is not significant for most plotting

SINX/X

ROW 1: LINES 1-4

ROW 2: LINES 5-11

Fig. 4. *Bar-code functions and powerful user language programs given in the 82184A Plotter Module's user manual make it easy to obtain plots of bar-code programs as shown.*

uses, but it is enough to slightly alter the geometry of the bar code produced. Thus, parameters set to produce suitable bar code with a new pen may later produce unreadable bar code as the pen begins to wear. Plotting discrete bars would have required the pen to be dropped as many as 1584 times for a single page of bar code. Pen wear caused by repeated nib impact against the paper is minimized by connecting all of the bars in a row at the top (Fig. 4), so that the pen is only lowered once at the start of a row of bar code. This also speeds bar-code production by eliminating the time delays associated with raising and lowering the pen.

Default parameters were chosen to produce the most consistently readable bar code for the widest range of pen nib conditions and ink flow. A 0.3-mm pen is assumed for these parameters and good results were obtained with both fiber tip and transparency pens. Recognizing that users may choose to use different pens and that the pen nib width changes with use, a command is provided to alter the bar code parameters. BCSIZE allows users to specify (in APUs) any or all of the bar-code parameters.

Creating bar code with the plotter module is a two-step process. Data is entered into either the X register or the ALPHA register of the HP-41C and then the appropriate bar-code function is executed. This creates the bit pattern of the desired bar code and places it in the ALPHA register. A second command, BC, must then be executed to plot the bar code on the 7470A.

Interactive Plotting Program

NEWPLOT is an interactive plotting program that can plot functions or any arbitrary set of points with minimum overhead. The program prompts the user for 1) the name of a user program that, given an X coordinate, will compute the Y coordinate, 2) scaling information, and 3) either the number of points to be plotted or the increment between points to be plotted. At that point the user can examine and edit any or all of the data base. The user can specify the placement of the X and Y axes, the number of major and minor tics per axis, and the number of labels per axis. Data buffers can be created, edited, and plotted. Other built-in features allow the user to alter the line type and pen used for plotting, and to do scatter plots. It is also possible to change one or more parameters of the plot and then to redo the complete plot with one keystroke.

Acknowledgments

Thaddeus Konar was primarily responsible for the bar-code plotting commands. Dave Conklin provided ideas and guidance throughout the project.

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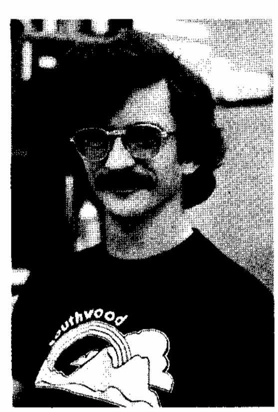
Robert M. Miller

Bob Miller joined HP after receiving a BS degree in computer science at California State Polytechnic University in late 1980. He also has a BA degree in English literature awarded in 1973 by LaSalle College, Pennsylvania. The HP-41C Plotter Module was his first HP project and now he is a project leader for HP-75C application software. Bob was born in Philadelphia, Pennsylvania and now lives in Corvallis, Oregon. His interests include backpacking, reading, swimming, and playing volleyball.



Randy A. Coverstone

Randy Coverstone was born in Goshen, Indiana, and attended the University of Evansville, Indiana, receiving a BSME degree in 1975. After earning an MSME degree and the degree of Mechanical Engineer at the Massachusetts Institute of Technology in 1978, he joined HP. Randy worked on the chart advance for the 9872 Plotter, which he discussed in an earlier HP Journal article, and the servo design of the 7470A. He is a visiting lecturer on applied controls at the University of California at San Diego. He is married, has a new baby daughter, and lives in San Diego, California. His outside interests include designing recumbent bicycles and playing works by Bach and Scott Joplin on the piano.

Low-Cost Plotter Electronics Design

by Neal J. Martini, David M. Ellement, and Peter L. Ma

THE ELECTRONICS for the 7470A Graphics Plotter had to be designed as inexpensively and ruggedly as possible to remain consistent with the philosophy of a low-cost, high-performance, high-reliability product. The basic guidelines for the design were to use a single printed circuit board for the entire electronic system, minimize overall parts count, eliminate the need for a cooling fan, and use custom and semicustom electronics with high performance/cost ratio wherever possible.

Fig. 1 is a block diagram of the electronic design of the 7470A. All of the circuitry is contained on a single, two-layer printed circuit board 178 mm wide and 298 mm long. The plotter intelligence is provided by a 1-MHz 6802 microprocessor, an 8K×8 ROM, and a 1K×8 RAM. Some of the main functions controlled by the program code stored in the ROM are:

- Servo vector generation and servo system control
- Interpretation and execution of the HP-GL* plotter programming language (scaling, character generation, windowing, line type, et cetera)
- I/O control for the HP-IB,** RS-232-C/CCITT V.24, and HP-IL*** interfaces
- Pen-lift control.

The outside world communicates with the plotter via an HP-IB control chip and buffers. This integrated circuit handles the bus protocol and allows the microprocessor to be free from normal data transfer overhead.

*Hewlett-Packard Graphics Language.
**Hewlett-Packard Interface Bus, HP's implementation of IEEE Standard 488 (1978).
***Hewlett-Packard Interface Loop (see article on page 16).

Servo

Two servos (Fig. 2) are used in the 7470A, one to move the paper and the other to move the pen carriage. The electronics for this consists of the microprocessor generating and sending digital move commands to the VLSI NMOS servo chips via the CMOS gate arrays. The two gate arrays contain all the circuitry needed to support the VLSI circuits and driver sections of the electronics (see box on page 25). The servo chips output pulse-width-modulated (PWM) and direction signals back to the gate arrays. The gate arrays take these signals and generate the appropriate signals to control the switching motor drivers. In addition, the gate array circuits modify the pulse widths to adjust the servo gain to compensate for power supply variations and stabilize the slow axis movement. As the mechanical system moves, optical encoders (see article on page 26) mounted on the back of each dc motor send back digital pulses to the servo chips to close the servo loops.

Regulating the motor supply voltage would have been a duplication of effort because the servo already modulates this voltage, usually to an average value less than full supply voltage. It is less expensive to adjust the servo gain to compensate for power supply variations. For the gate array logic to know how much to change the servo chip pulse width, the microprocessor must know the level of unregulated voltage supplied to the motors. A voltage sensing circuit, consisting of a 1-bit analog-to-digital converter, provides this data. The output of the converter also serves the dual purpose of controlling the front-panel error light.

The servo system (Fig. 2) was modeled as a third-order system, with two-state feedback. The electrical time con-

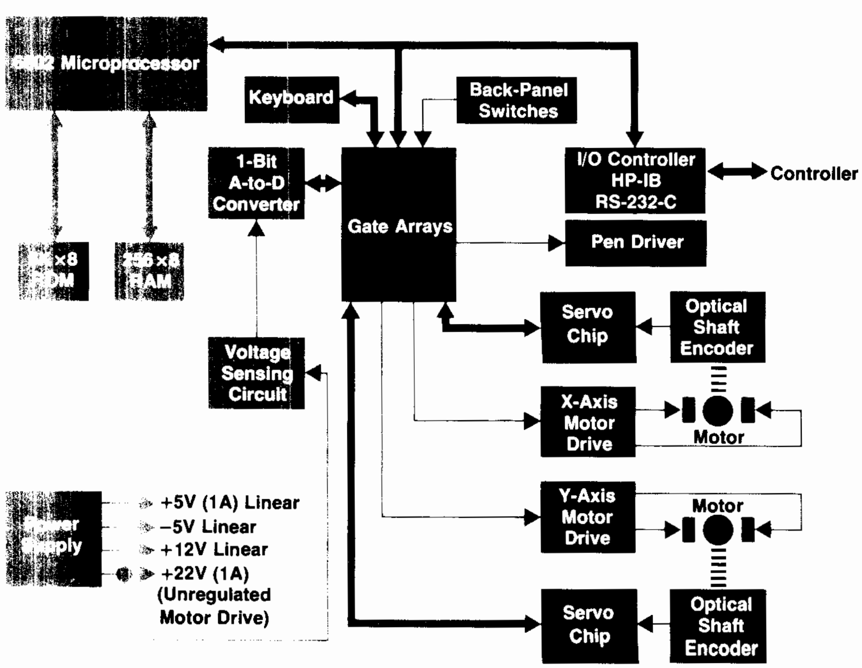


Fig. 1. *Block diagram of electronic system for the HP 7470A Graphics Plotter. Most of the system logic is implemented by two custom gate-array ICs.*

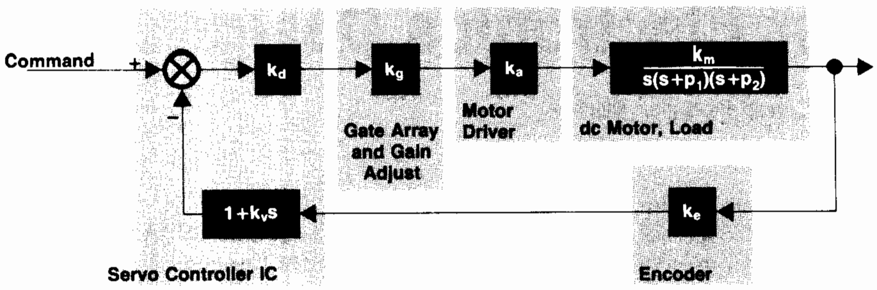


Fig. 2. *Block diagram of servo system for each plotting axis in the 7470A. Pulse-width-modulation (PWM) drivers are used because their switching action offers much greater efficiency than linear drivers. This reduces power consumption and heat generation.*

stant of the dc motor is such that it could not be neglected. However, adequate performance is achieved with only position and velocity feedback.

A servo controller IC supplied by HP's Corvallis Division[1] is used to close the loop. It provides the interface to the microprocessor, decodes the encoder signals, sums position errors, estimates velocity and sums it, and transforms the servo error to a pulse-width-modulated output. The velocity constant and PWM gain, both IC mask programmable, were changed to adapt the original servo controller chip to this servo system.

The PWM output of the servo chip is processed in the gate array to provide an adjustable forward path gain k_g. There are two reasons why it is necessary to adjust the gain. First, because the motor driver supply voltage is unregulated, the forward gain k_a through the motor driver varies with its supply voltage. This variation is too wide to maintain adequate performance without compensation. Second, below some threshold velocity, the servo controller chip provides no velocity feedback. This leaves the servo underdamped, and enhances limit cycling. Reducing the forward gain when the servo is idle reduces this effect. Through the gate array, the processor can control the forward gain and compensate for both problems.

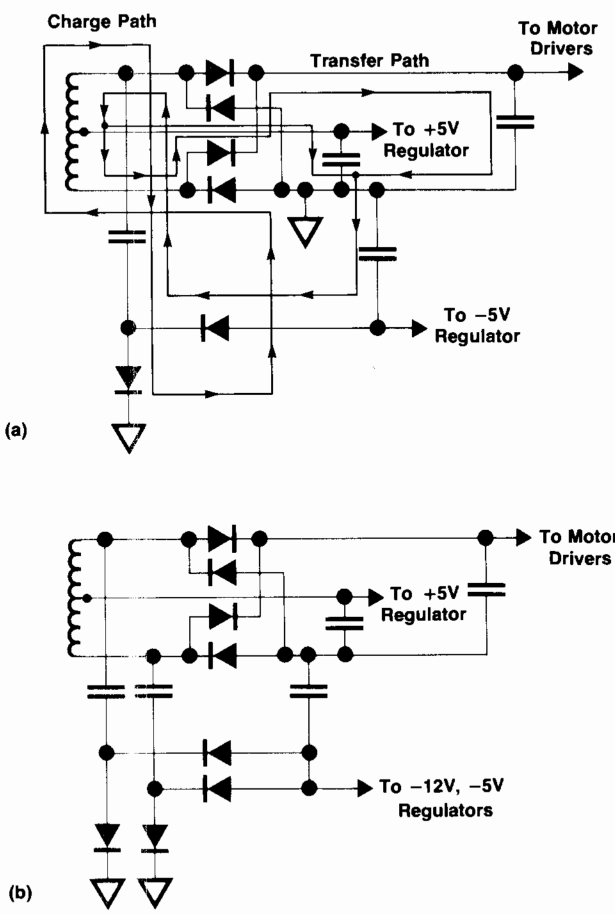


Fig. 3. *Charge pump circuits are used to supply negative voltages for servo and I/O circuits. (a) Half-wave pump for HP-IB and HP-IL versions of 7470A. (b) Full-wave pump for RS-232-C/CCITT V.24 version.*

Pen Lift

The pen lift in the 7470A is actuated by a solenoid. To minimize the size of the solenoid it is necessary to drive it first with one current to pull the plunger in, and then with a smaller current to hold it in. This is accomplished by a PWM voltage drive. The PWM duration is set by the gate array logic. One duty cycle is used for pulling in and another for holding. These duty cycles are under microprocessor control and are modulated to eliminate the effects of unregulated 24Vdc supply variations.

Power Supply

Four voltages are generated by the power supply module. Low-current supplies provide the +12V and −5V required for the NMOS servo chips. These supplies are also used in the RS-232-C/CCITT V.24 version of the 7470A. In addition, there is a linear 5V supply. The linear supply design is attractive because of its simplicity, and can be used because the total 5V load current is low, nominally 600 mA (the CMOS gate arrays and the NMOS servo chips require very little power). The fourth voltage is the unregulated +24Vdc supplied to the main drive motors. Since this voltage has to supply about 1 ampere rms, it is less expensive if it does not have to be regulated. This is possible because of the voltage-sensing and servo gain adjust schemes described above.

To supply the negative voltages required for the I/O and the servo chips, charge-pump circuits (Fig. 3) were chosen to run off the secondary of the transformer. A half-wave pump is used for the HP-IB and HP-IL interface versions of the 7470A. The RS-232-C/CCITT V.24 version requires a full-wave pump. The part sizes for operation at the low-frequency limit of 47 Hz were acceptable, so there was no need to consider operating at a higher frequency. The extra parts needed for the charge pumps cost less than adding an extra transformer winding.

Custom IC Electronics for a Low-Cost Plotter

It was apparent early in the development of the 7470A that there was a need to integrate much of the electronics. The digital portion most readily lends itself to integration in some form of custom IC. The analog circuits, on the other hand, were designed with off-the-shelf parts, but nevertheless benefited from the use of commercially available ICs.

In deciding which part of the digital electronics should be made into a custom IC, we noticed that the microprocessor, memory, I/O controller and buffers, and the servo controllers were all in LSI (large-scale integration) form already. Our strategy, then, was to try to eliminate all of the 74LS-series ICs from the printed circuit board. This has many attractions:

- A custom LSI IC saves a tremendous amount of board space
- Substantially less power is required from the power supply and less heat is generated
- Electromagnetic compatibility requirements can be met more readily because the radiation caused by the relatively short rise and fall times of LSTTL* signals and many interconnecting traces on the printed circuit board are eliminated.

Gate Arrays

After the decision was made to develop a custom IC, we had to select between the different technologies available. The selection process was based on many important factors that include: per piece part cost, development cost, development time, expected volume, circuit complexity, reliability, and design risk. A fully custom NMOS (n-channel metal-oxide-semiconductor) integration effort was considered. This approach promised relatively low part cost using proven technology and design methods. However, the very high development cost and lengthy development time could not be justified at our projected moderate volumes.

We turned to another approach—semicustom gate arrays, which are rapidly gaining in popularity. Gate arrays are integrated circuits prefabricated in wafer form up to the final processing steps. These wafers are then customized at the metal masking stage by applying a unique interconnect pattern to implement the logic design. Because of the lower level of customization, shorter development time can be expected along with significant savings in development cost.

Based on the large amount of circuitry to be implemented in LSI form and the number of signal pins required, two silicon-gate CMOS (complementary metal-oxide-semiconductor) gate arrays were selected. The silicon-gate process provides the necessary performance level, and the use of CMOS logic reduces power consumption to a very low level. Of the two arrays chosen, one is a 770-gate array and the other contains 1000 gates. Both are housed in low-cost 40-pin dual-inline plastic packages. These two arrays are the equivalent of 80 LSTTL ICs that would have required a current of 0.7A at 5V. As a result, the HP-IB version of the 7470A contains only eleven digital ICs, quite amazing considering its performance and capabilities.

Armed with the strategy of attempting to put every little bit of miscellaneous digital circuitry in the gate array implementations, we began development of the array ICs. First, the circuits were designed using standard 74LS-series ICs. After breadboarding and testing was performed to check out the design, a gate count was done to determine the array size required. The resulting total gate count of 1200 precluded the use of one large array. Instead, two moderate sized arrays were chosen. The circuits were then partitioned for a good fit in the following way. The circuit functions for gate array A include the baud-rate generator, interrupt timer, servo control and status ports, memory decode, Y-axis motor drive control, and Y-axis servo gain adjust. The circuit functions in gate array B include the pen solenoid pulse-width modulator, power supply voltage measurement circuit, front-panel input ports, memory decode, X-axis motor drive control, and X-axis servo gain adjust.

During the development of the gate array ICs, the LSTTL version of the gate array circuitry was made into printed circuit boards. These boards served as logic simulators for the ICs, allowing the prototype 7470A instrument to operate while the ICs were in development. These boards plugged directly into two 40-pin sockets on the instrument board via ribbon cables. When the gate array ICs were ready, the boards were replaced.

-Peter Ma

Peter L. Ma

Peter Ma joined HP in 1978 and designed the I/O processor system for the 7310A Printer and the digital circuits and gate arrays for the 7470A. He is a graduate of the University of Washington, where he received a BSEE degree in 1978, and Stanford University, where he received an MSEE degree in 1982. Peter was born in Hong Kong and grew up in Seattle, Washington. He is a high-fidelity audio enthusiast, enjoys tennis, skiing, and going to the beach, and lives in San Diego, California.

David M. Ellement

David Ellement received the BSEE degree in 1976 from the University of California at Berkeley and joined HP shortly after. Besides his work on the 7470A, he developed the 7245A's power supply. David was born in Buffalo, New York and is a member of the IEEE. He is married, has one daughter, and lives in Escondido, California. When not busy improving his mastery of the local Spanish dialect, David enjoys soccer, cross-country skiing, and bouldering.

Neal J. Martini

Neal Martini has been with HP since 1978 and was the electronics project leader for the 7470A. He received a BSEE degree from the University of Detroit in 1969 and the MSEE degree from the University of Missouri at Rolla in 1971. Born in Buffalo, New York, Neal now lives in San Diego, California. He is married, has two children, and enjoys playing racquetball, tennis, basketball, and piano.

Acknowledgments

Special thanks to the following for their contributions to the 7470A development: Dave Paulsen and Janie Chintala for their outstanding software contributions, Gary Skrabatenas for his motor driver and power supply designs, Richard Murray for his work in the I/O area of the 7470A, Keith Cobbs for his analysis and testing of the servo design, Dee Setliff for her contributions to the RS-232-C code development, and Bruce Jenkins for his help in following through with the HP-IL version of the 7470A.

Reference

1. C.C. Lo, "Plotter Servo Electronics Contained on a Single IC," Hewlett-Packard Journal, Vol. 32, no. 10, October 1981.

Plotter Drive Motor Encoder Design

by Arthur K. Wilson and Daniel E. Johnson

The 7470A Graphics Plotter uses dc motors for pen and paper positioning and optical encoders for position feedback. To achieve good graphic output at a low cost, the plotter drive system requires encoders with the following capabilities:

- Two-channel output for determining direction
- 500-line count per channel
- 500 r/min maximum motor speed
- ±25 degree phase accuracy per channel.

In addition to these requirements, the 7470A project design team had two main objectives: low cost and high reliability.

To achieve low cost we used:

- A special motor with a built-in endbell to house the encoder assembly (Fig. 1). This allows us to install the encoder directly on the motor with no additional machining or related mounting costs.
- An etched stainless-steel code wheel and phase plate. By using an etched code wheel with a closely toleranced bore, we were able to use a low-cost part and also eliminate the requirement of having to center it on the motor shaft.
- Self-stick adhesive bonding of the code wheel to the hub and pressfit of the code-wheel-hub assembly on the motor shaft. These two features eliminate the need for gluing fixtures and the labor, time, and space required for this procedure. We also press the code-wheel-hub assembly on the motor shaft to its correct location before adding the optics assembly. This eliminates having to adjust the code-wheel-to-phase-plate spacing

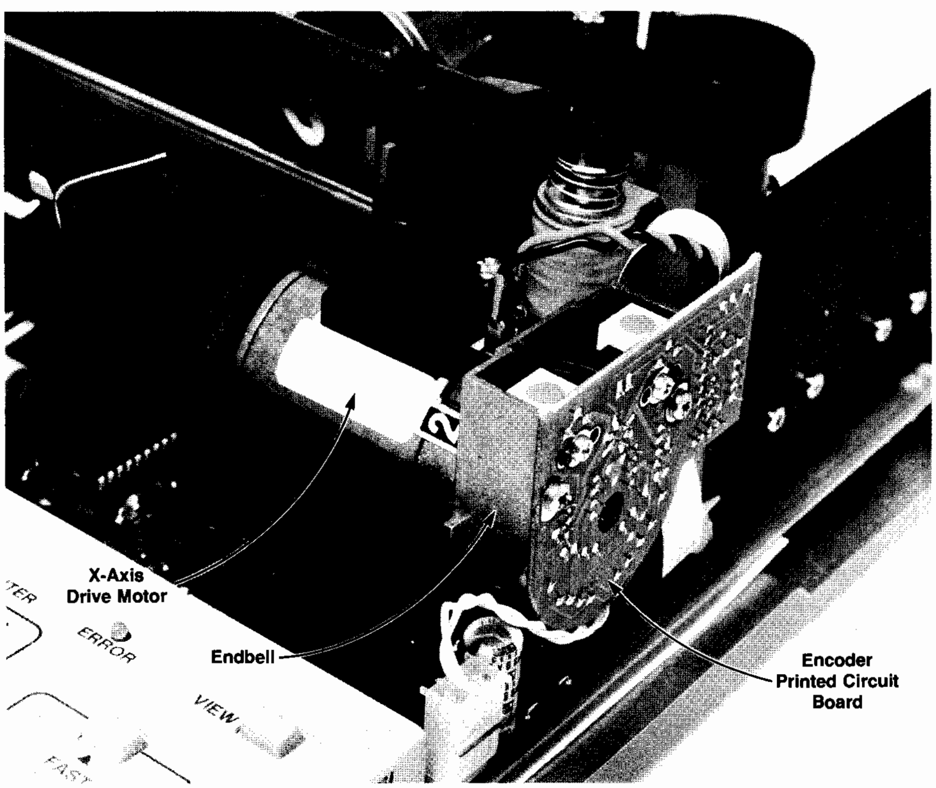


Fig. 1. *An optical encoder is mounted in a custom endbell on each dc drive motor, forming a compact assembly as shown.*

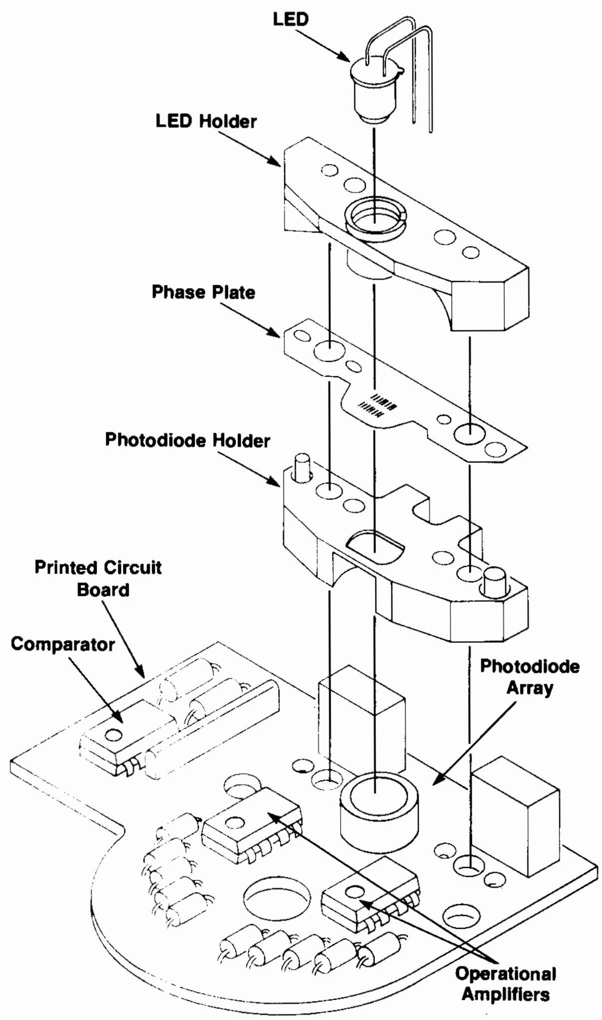


Fig. 2. *Exploded view of encoder's optical and electronic assembly.*

after the optics assembly has been mounted.

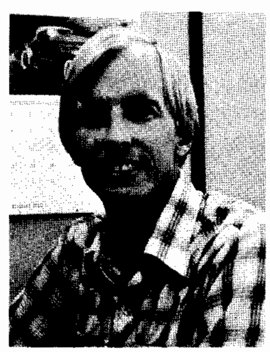
- Custom components such as special resistor networks where applicable. This saves considerable space on the printed circuit board, has a lower net cost, and reduces lead lengths in low-level signal areas, minimizing electrical interference problems.
- Standard components with standard tolerances when possible. For example, using standard-size composition resistors with 5% tolerance reduces both material cost and, by making it possible to use automatic insertion machines, labor cost.
- Test and assembly tooling to minimize assembly time. For example, the printed circuit boards are fabricated, loaded, and tested ten at a time. Then, during final assembly, the encoder is adjusted to ±10-degree phase accuracy using a specially designed test fixture.

To meet the high-reliability objective the encoder design (Fig. 2) uses the following;

- A single light-emitting diode for the light source.
- A custom detector consisting of a single monolithic chip with four matched photodiodes driven in the short-circuit mode.
- A dual operational amplifier to drive a voltage comparator on each channel.
- Collimated see-through method of light sensing that allows for tolerant code-wheel-to-detector-plate spacing.
- Solid mounting of optics holder to endbell assembly. Careful attention was given here to make sure that the optics holder would not move or drift and become misaligned. Also we brought the sides of the endbell up and mounted the encoder optics assembly upside down compared to the way it is generally done. This allows us to assemble the encoder easily down onto the motor without the fear of damaging the code wheel.
- A specially designed fixture that simulates an actual encoder to test the optical components to ensure operation under worst-case conditions.

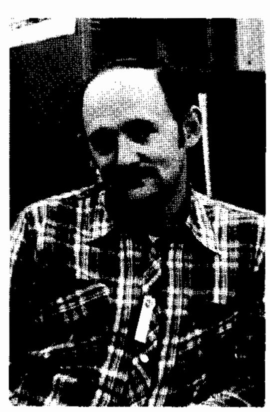
Acknowledgments

We would like to acknowledge Choung Ta for his efforts in designing and testing the optical holder and components, code wheel, and phase plate as well as his efforts on the printed circuit board layout, which was inseparable from the product design of the overall encoder. Also, we would like to thank John Powell for his contribution in designing the encoder tester electronics.



Arthur K. Wilson

Art Wilson received an MS degree in mechanical engineering from the University of Arizona in 1970. He joined HP that same year as a design engineer. His most recent work has been the development of the 7470A's optical encoders. He was born in Tucson, Arizona, is married, and has one son. Now living in San Diego, California, Art enjoys restoring antique automobiles—his current project is a 1909 two-cylinder Maxwell.



Daniel E. Johnson

Dan Johnson was born in Washington, D.C. He attended Lafayette College, Pennsylvania, earning a BSEE degree in 1965, and the Polytechnic Institute of New York, earning an MSEE degree in 1967. He came to HP in 1970 and has made contributions to the 7040 family of X-Y recorders and, more recently, the optical encoders for the 7470A. Dan has written one other article for the HP Journal, and is a member of the IEEE and vice-president of the San Diego chapter of the California Society of Professional Engineers. He is married, has two sons, and lives in Poway, California. When he is not busy coaching Youth Soccer and Little League, Dan enjoys travel, camping, reading, sports, and playing in HP's local softball league.

Graphics Plotter Mechanical Design for Performance and Reliability at Low Cost

by Richard M. Kemplin, David M. Petersen, Chuong C. Ta, David C. Tribolet, and Robert J. Porcelli

THE MECHANICAL DESIGN of a graphics plotter is a major factor in determining the plotter's cost, performance, and reliability. Although digital electronic techniques can replace the majority of mechanisms such as cams, springs, dashpots, and limit switches used in earlier plotters for control functions, paper handling and pen positioning must still be done mechanically.

The plotting and pen handling mechanisms used in the 7470A Graphics Plotter are designed simply with a minimum of parts, yet provide reliable, high-quality output. Movement along each plotting axis is handled separately to reduce mechanical complexity. The pen carriage can select either of two pens stored in stalls located on opposite edges of the paper.

Y and Z Axes

Patterned after the Y axis of the original "Sweetheart" mechanism developed by HP Laboratories,[1] the Y axis of the 7470A is driven by a dc motor and optical encoder assembly. A drive pinion, timing belt, and idler pulley make up the power transmission loop, the belt being attached to a slider block assembly which holds the pen. The Z-axis pen-drop mechanism is a rotational spring mass and damper system. To write, the pen is allowed to fall and rest on the paper. The pen is lifted as needed for nonplotting movement.

The design of the Y and Z axes uses the existing line of HP plotter pens, whose delicate fiber tips can be easily crushed upon pen-drop impact, producing an undesirably wide ink line. The inertia and impact velocity dictated by the pen size indicated that pen-drop damping was required to avoid fiber tip damage. The pen-change system dictated a pen holder with complex detail and tight tolerances. Servo performance required keeping the pen-drop mechanism and slider-block masses low as well as minimizing Y-axis friction and deadband.

The pen holder, one of the two main parts of the slider block (Fig. 1), uses snap-in bushings machined from Delrin™ A.F.* and mounts directly on a stainless-steel slider rod centerless-ground to a precise diameter. It moves along the rod for Y-axis displacement and rotates about the rod for Z-axis movement. Mounting the pen holder on the rod instead of the carriage, the second main part of the slider block, reduces the number of interfaces locating the pen to the platen, thus reducing rotational deadband.

The carriage of injection-molded Delrin A.F. rides on both the slider rod and a parallel hard-anodized Teflon™-coated aluminum extrusion (see Fig. 1 and Fig. 2). A compression spring placed between the carriage and the pen holder, coaxial with the slider rod, preloads these parts together, removing deadband without increasing Y-axis friction.

*An acetal homopolymer containing 20% polytetrafluoroethylene.

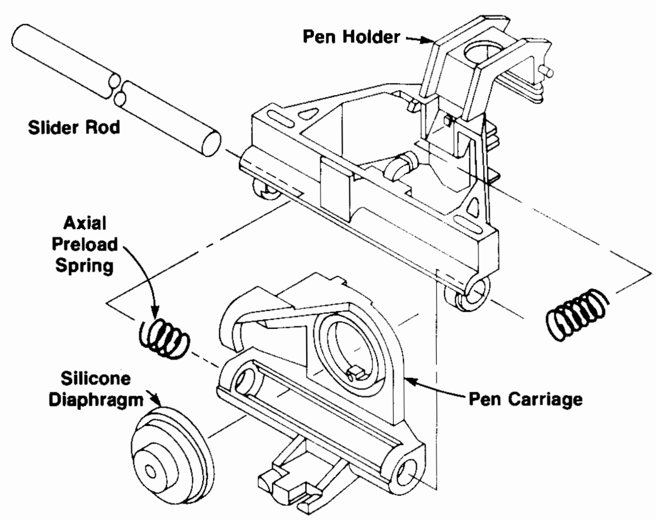


Fig. 1. *Exploded view of slider block assembly used to transport the pen along the Y-axis of the 7470A Graphics Plotter.*

Tension in the drive belt is maintained by a spring-loaded tensioner ramp on which the idler pulley shaft rests (see Fig. 3). The ramp shifts to compensate for changes in belt length caused by temperature or creep, but a low ramp angle and friction prevent the spring from entering the Y-axis dynamic system. The tensioner and idler pulley are retained by belt tension and the spring. The belt attaches to the slider block by looping around a half gear detailed in the carriage, relying on belt tension to hold it in place.

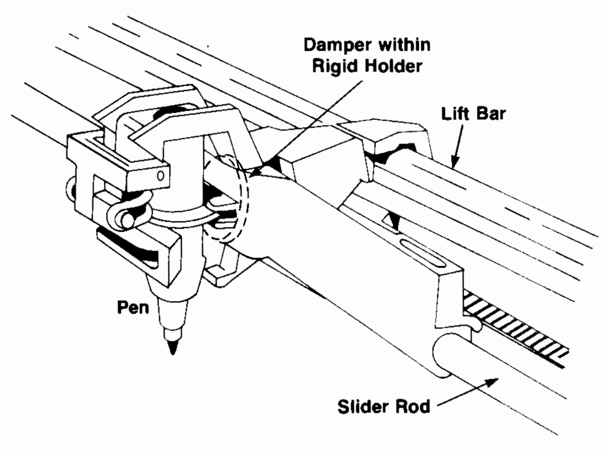


Fig. 2. *Pen transport mechanism. The slider block is supported and accurately guided by a centerless-ground stainless-steel rod. The slider block is restrained from rotating about this rod by an aluminum lift bar whose rotation raises and lowers the pen.*

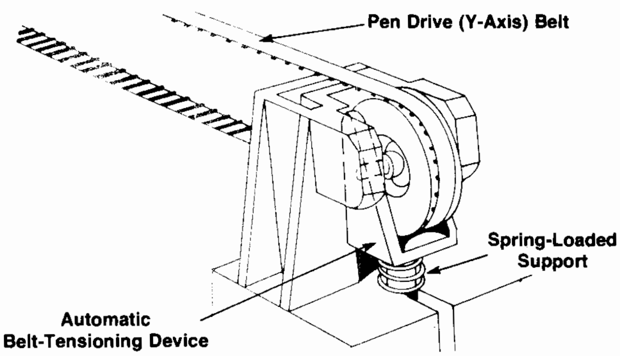


Fig. 3. *Pen-drive-belt tensioner mechanism.*

The pen lift is activated by a solenoid. Held to the main chassis with one screw, it lifts and drops the pen by rotating the aluminum extrusion. It also retains the extrusion and plastic linkage parts. Mounting the solenoid off the slider block greatly lowers slider block mass and reduces parts count and cost by not requiring a flexible trailing cable. Off-axis mounting also removes size and shape constraints, allowing a low-cost, large, mass-produced solenoid to be used.

A compression-molded silicone diaphragm pressed into the mounting detail on the carriage performs as a bellows damper (see Fig. 2). During a pen drop, the solenoid rotates the aluminum extrusion so that the pen holder is free to fall. As the pen holder descends it deflects the diaphragm. This provides viscous damping by forcing air through a 5-mm-long, 0.4-mm-diameter hole molded into the carriage.

During the initial development of the Y axis, friction and deadband were found to be unacceptable. The idler pulley design changed from a simple plastic wheel on a steel dowel pin to a pulley pressed onto a Class 1 ball bearing. This reduced Y-axis friction by 15%. The preload spring was added between the carriage and pen holder to reduce translational deadband and silence a noticeable servo buzz. Extensive life and Class-B environmental testing showed that the pen-holder bushing clearances could be reduced to 0.025 mm, well below the manufacturer's recommendations. This helped reduce both rotational and translational deadband. Finally, to improve line quality further, two deadband compensation algorithms were implemented in firmware. One is used to correct for axis reversal deadband, adding or subtracting this amount with each axis direction reversal. The second, a static friction compensation, helps ensure that the X and Y axes begin to move simultaneously. This is done at the start of each plot vector by preloading each servo error register with enough encoder counts to set up a condition of impending motion on each axis. Each axis starts to move with the first count of the reference signal to that axis. Without this compensation, an axis would not break away until enough error counts built up to overcome axis static friction. This delay could produce severe hooks at the start of low-angle vectors when the rate of incoming reference counts to each axis can be very different.

Early prototypes showed that the pen-holder inertia and high stiffness in the pen's fiber tip resulted in a pen-suspension natural frequency that was very sensitive to paper roughness. Instead of tracking the paper, the pen would skip over paper bumps, leaving dashed ink lines.

This pen skipping was eliminated by getting the paper to track the nib and by reducing the Z-axis natural frequency. A 0.4-mm-deep and 4-mm-wide groove was molded into the platen under the line of pen-tip travel. The portion of the paper bridging the groove deflects under the pen's 20-gram writing force, in effect placing a low-stiffness leaf spring in series with the high-stiffness pen fiber tip. The pen-suspension natural frequency is considerably lowered, and more important, over the deflection range of the paper, the paper tracks the pen tip as it moves up and down.

The pen-holder design required a plastic that would provide:

- High material stiffness and strength to allow a low-mass part
- Excellent processing and dimensional stability to allow tight tolerances to be held for pen-change interfacing requirements
- Lubricity for low sliding friction
- A low wear rate for long service life.

Polycarbonate with 30% glass fiber and 15% Teflon was selected. Its remarkable insensitivity to processing variations allowed holding a tolerance of ±0.1 mm on an open section over a 40-mm length with reasonable ease. It met the above goals well with high pressure-velocity limits and dimensional stability, allowing bushing-to-slider clearances as low as 0.008 mm on a 6.4-mm-diameter slider rod over an operating temperature range of 0°C to 65°C. Unfortunately, it became apparent that 30% of the machines after life-testing emitted a loud squeaking noise from the pen-holder bushings. Experiments varying bushing geometry and shaft surface roughness and employing lubricants failed to quiet the squeak. The cost-and-clearance compromise solution uses screw-machined bushings of Delrin A.F., which are snapped into place.

X Axis

In the 7470A, small-diameter grit-covered wheels move the plotting medium in the X direction, obviating the need for many of the massive components typically found in the X axes of fixed-media plotters. Hence the paper-moving

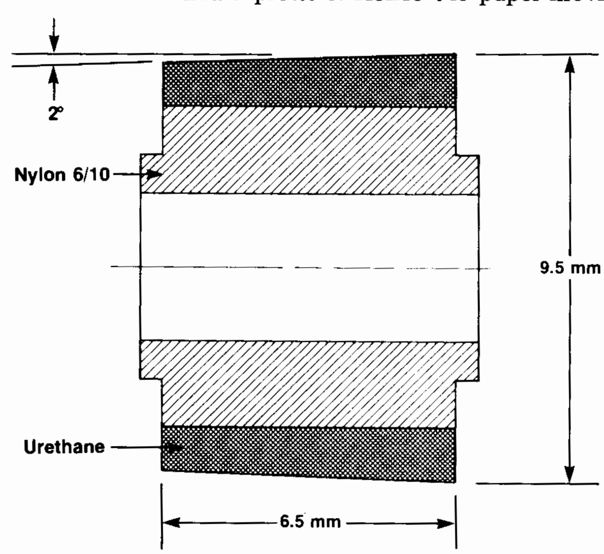


Fig. 4. *Cross section of tapered pinch roller.*

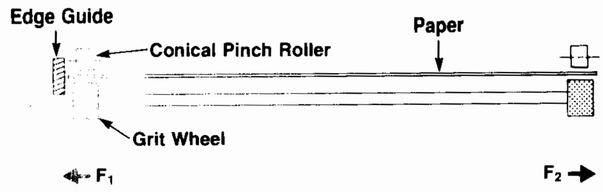


Fig. 5. *The plotting medium is kept flat by using tapered pinch rollers as shown. The difference in forces F1 and F2 keeps the medium registered against the edge guide on the left.*

approach yields an inherently low-inertia X axis. This in turn permits the use of smaller, lower-cost drive motors. In addition, a low-inertia X axis makes the task of high-performance servo design somewhat easier and reduces power consumption.

The cornerstone of the 7470A's paper drive is the micro-grip drive mechanism previously described in the November, 1981 issue of the *Hewlett-Packard Journal*.[2] In this scheme, two opposite edges of the plotting medium are each pinched between an aluminum-oxide-coated drive wheel and a pinch wheel. As the drive wheels rotate, the aluminum-oxide particles form minute depressions in the surface of the plotting medium, thus producing a drive track which can be followed on successive passes of the medium through the plotter. Ideally, each depression always realigns with the same aluminum oxide particle that created it. As a result of the tracking ability of the micro-grip drive, the 7470A achieves a repeatability of 0.1 mm with any given pen.

In plotters with a pen-lift system, paper flatness is a key design specification. A plotter with poor paper flatness must use a higher pen lift to avoid inadvertent marking during pen-up moves. A large pen-lift height increases the time required to raise and lower the pen, thus impairing plotter throughput.

The 7470A uses a new approach to maintaining paper flatness—tapered pinch rollers. The tapered roller consists of a nylon hub beneath an elastometric polyurethane cover having a two-degree taper (Fig. 4). When a sheet of paper is driven between the grit wheel and the conical pinch roller, the paper tends to move laterally toward the large-diameter end of the roller. Thus, if the pinch rollers are oriented with their large diameters toward the edge of the paper sheet, they cross-tension the paper as it is driven back and forth (Fig. 5).

The manner in which the conical roller moves paper laterally toward its large-diameter end depends on the fact that the rubber in the pinch roller is displaced sideways when pressed against the paper (Fig. 6a). This creates a contact patch like that shown in Fig. 6b. Now consider a particle of polyurethane on the large-diameter surface of the pinch roller. As the pinch wheel rotates, this particle comes into contact with the paper and traces out a path resembling that shown in Fig. 6c. As the particle moves out to its maximally displaced position, it exerts a frictional force on the paper acting to the left. Conversely, as the particle moves back from its maximally displaced position, it exerts a frictional force on the paper to the right. But, because of hysteresis in the polyurethane, the sum of the forces acting to the right is less than the sum of those acting to the left. Hence, there is a net force to the left, that is, toward the large-diameter end of the tapered roller.

Tapered pinch wheels have several advantages over conventional methods of achieving paper flatness. First, tapered pinch wheels are a low-cost solution since paper flatness is achieved not by adding parts, but rather by changing the shape of an existing component. The tapered rollers can be easily fabricated by injection molding because their conical shape can be readily removed from the mold. In addition, by using a larger pinch force on one side, the paper can be kept aligned against a reference edge located on the side with the higher pinch force. This eliminates the problem of lateral paper walking.

Early in the 7470A's development it became clear that the X-axis was inherently a lower-inertia mechanism than the Y-axis. However, servo design is simplified if the two axes have equivalent inertias, since this helps ensure that both axes have the same dynamic and steady-state error behavior. Inertia matching was achieved by incorporating a large-diameter flywheel into one of the three parts used to couple the X-axis motor to the drive-wheel shaft. Since the coupler part with the flywheel is injection molded, the cost of inertia matching is very low.

Pen-Changing Mechanism

Multicolor and multipen plotting is clearly a desirable feature in a hard-copy graphics device. Conventional approaches to multicolor graphics include pen turrets, off-carriage pen arrays and on-carriage pen arrays. Pen turrets[3] can be used to store a large number of pens and are well-

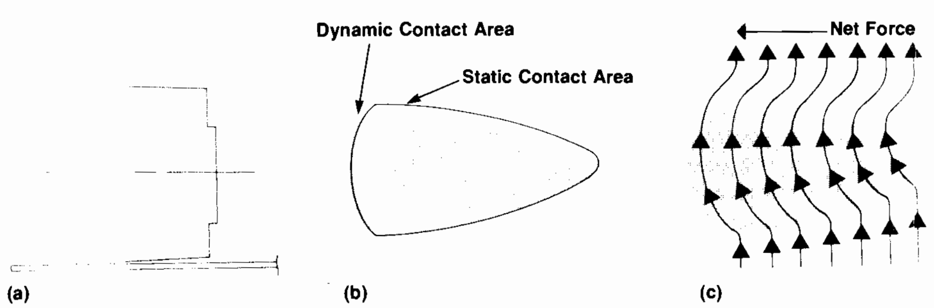


Fig. 6. *(a) Cross section of tapered pinch roller showing deformation where it is pressed against the paper. (b) Magnified outline of static and dynamic contact area between the roller and the paper. The asymmetry in the dynamic contact patch is caused by hysteresis in the deformed roller. (c) Dynamic contact area shown in (b) with the paths of particles on the surface of the roller indicated. These paths result in a net force to the left as shown.*

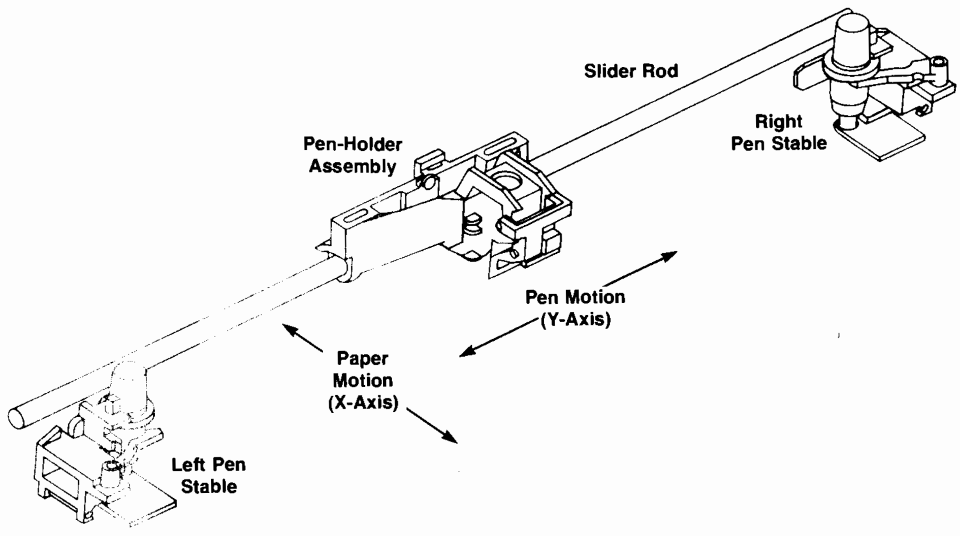


Fig. 7. *Basic Y-axis configuration showing the pen carriage and location of the two pen stables.*

suited to plotters with only one axis of carriage motion. However, pen turrets tend to be somewhat expensive. Off-carriage pen arrays[4] are likewise capable of storing a large number of pens but require two axes of carriage motion. On-carriage pen arrays burden the carriage with extra mass which compromises servo performance. In addition, more than one pen holder on the carriage introduces tolerances from holder to holder. Hence, some degree of repeatability from pen to pen is sacrificed.

Since none of the existing schemes for achieving multi-pen plotting seemed well-matched to the 7470A's low-cost product objectives, a different approach was taken. The basic configuration is shown in Fig. 7. The main elements of the pen-changing mechanism are the left pen stable, the right pen stable, and the pen-holder assembly. Each stable houses one pen and caps the nib to prevent drying. Note that the pen stables are mirror images of each other and the pen-holder assembly is symmetrical.

Each stable consists of four components: the stable housing, the stable arm, the capper arm and a garter spring. The stable housing positions the pen and provides structural support for the other stable components. The stable arm holds the pen against the stable housing. The capper arm seals the pen nib from ambient air and is actuated by a ramp built into the pen holder. The garter spring holds the stable arm in place and provides the pen holding and capping forces. The stable housing, stable arm and capper arm are injection molded to minimize cost.

The pen-holder assembly consists of two pen-holder arms, a garter spring and the pen holder itself. The pen-holder arms position the pen against the pen holder while the garter spring provides the pen-holding force to both arms. The pen holder positions the pen and provides structural support to the other pen-holder elements. Fig. 8 illus-

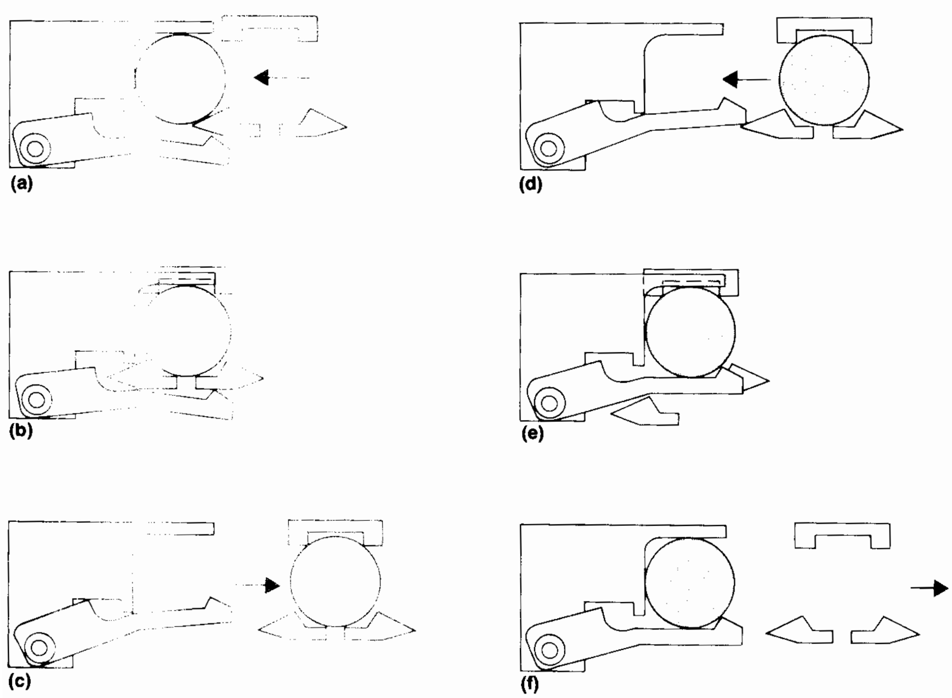


Fig. 8. *Pen pick (a through c) and pen park (d through f) sequences showing interaction between pen holder arm and the pen stable arm.*

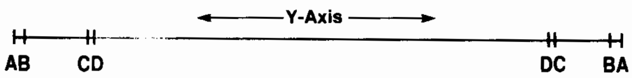


Fig. 9. *Location of pen-carriage stall positions A, B, C, and D (defined in text) along the Y-axis.*

trates how the various pen-changer components interact during a pen pick (Fig. 8a to 8c) and during a pen park (Fig. 8d to 8f). The intermeshing arm concept illustrated in Fig. 8 was first used in the HP 7580A Drafting Plotter,[5] but in a unidirectional configuration.

Pen Sensing

In multipen plotters such as the 7470A, it is important for the plotter to know where all the pens are. This prevents such undesirable events as trying to write without a pen, selecting a nonexistent pen, selecting the wrong pen and jamming two pens into each other. When the 7470A is powered up, a pen could exist in any or all of three locations: the left stable, the right stable, and the pen holder. It is a desirable feature if the plotter can identify where all the pens are without requiring the customer to power up the machine with a specific pen configuration. In addition, it is desirable if the plotter can detect a new pen configuration after initialization. Earlier solutions to the pen-sensing problem included the use of mechanical switches and optical detectors, but these schemes entail added cost as well as reduced reliability.

A completely new scheme for sensing pens was developed for the 7470A. This scheme uses Y-axis servo position error in combination with mechanical stops in the pen stables to assess where pens are and are not present. The Y axis is driven by a dc motor in conjunction with an optical encoder, which gives a position resolution of 0.025 mm. Hence, each count on the servo equals 0.025 mm of carriage motion. The Y axis is said to stall or saturate when the servo position error reaches 48 counts. This occurs when the pen carriage hits a mechanical stop, such as a surface in the pen stable. Fig. 9 shows the various pen-axis stall positions. Note that the carriage stalls in a unique position for each of the four cases: A, parking a pen in the stable; B, picking a pen from the stable; C, no pens in both the stable and holder; and D, pens in both the stable and holder. This is possible because the positions of the stable arms and pen-holder arms depend on whether or not a pen is present. Thus, various mechanical stops present themselves to the carriage based on the relative positions of the stable and pen-holder arms (Fig. 10).

Since a pen may exist in any or all of three locations, there are eight possible ways pens could be configured upon power-up. An algorithm in the 7470A's electronics determines where all the pens are by simply using the various pen-changer stall positions to deduce which of the eight possible pen configurations has been set up.

Chassis

On the injection-molded chassis are mounted all the mechanical parts for the operation of the pen-carriage and paper-mover servomechanisms and the pen-lift system. In addition, it functions as an enclosure for the electronics and is cosmetically visible to the user (see Fig. 2 on page 14).

As the main structural member of which many close tolerances are required, high strength and processing repeatability are critical. Maintaining a flat drawing surface

David M. Petersen

David Petersen was born in Palo Alto, California. He joined HP in 1978 and worked on the Y axis and pen lift of the 7470A. He is a member of the ASME and has a BSME degree (1978) from California State Polytechnic University. He is returning to school to earn an MSME degree at the University of California at Davis through HP's Fellowship Program. David is a cycling enthusiast and is working on a recumbent bicycle design. His other interests include spending time with his family, sailing, and beekeeping. David is married, has two sons, and lives in Escondido, California.

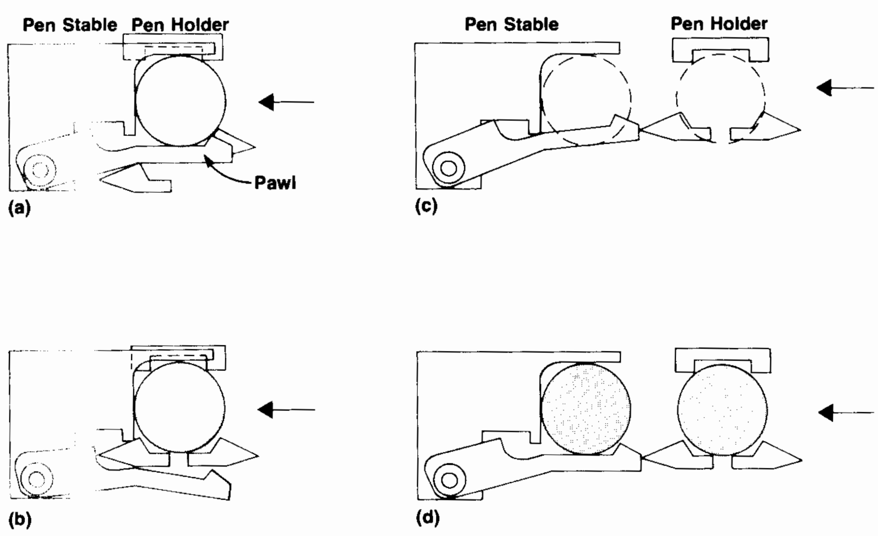


Fig. 10. *Diagram of interaction between the pen holder and the pen stable at the four stall positions. (a) Parking, Case A. Note that the pen holder travels farther into the stable in parking than in picking. (b) Picking, Case B. (c) No-pen-to-no-pen interference, Case C. (d) Pen-to-pen interference, Case D. Note that, because the tip of the pawl describes an arc about its pivot point, the pen holder travels slightly farther toward the stable if no pens are present than if two pens are present as in (d).*

with less than 0.3 mm of bow over a distance of 215 mm is important to pen-drop performance. Because it serves as the platen over which the paper moves, the chassis needs to be conductive with no more than $2000\Omega/\square$ surface resistance to bleed off electrostatic charge.

After evaluating several plastic formulations, a modified polyphenylene oxide containing 10% glass fiber, 10% carbon fiber (for conductivity), and 4% carbon black was specified for production. At first, this formulation was tried without the carbon black and it met the conductivity, strength, and platen bow requirements (production parts have less than 0.15 mm of bow over 215 mm). But, discouragingly, the glass and carbon fibers were well-displayed as light streaks in a sunburst pattern opposite the mold sprue gate located in the center of the platen. After brainstorming, the mold designers decided to move the sprue gate against a rear wall of the chassis, which greatly improved the uniformity of appearance, but not the color. Carbon fiber loading in plastic means you can have any color as long as it is a shade of gray or black. To achieve the uniform black color desired, we added the 4% carbon black to the base composition, which sufficiently hides the fiber streaks without making the part too brittle.

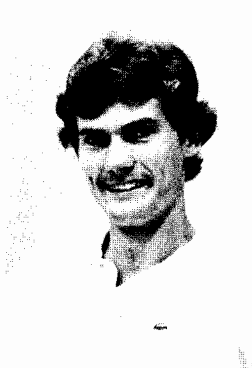
At this point in the plastic selection it was pointed out that the chassis' function as an ac-line-voltage electronics enclosure required that the plastic composition be Underwriters Laboratories (U.L.) flame-rated V-O. This was attempted by adding 20% of a flame-retardant filler. The result was a hopelessly brittle part with cosmetic blemishes. The U.L. requirement was satisfied in another way by modifying another part, used to mount the transformer, to enclose all line-voltage components in a V-O rated plastic.

Acknowledgments

The successful development of the 7470A mechanics was ensured by the insights, guidance and planning provided by Majid Azmoon. Product reliability could not have been achieved without the extensive life, strife and MTBF testing provided by Ned Bryant, Charles Shinner and the reliability group.

Robert J. Porcelli

Bob Porcelli has been with HP since 1973, when he received the BS degree in mechanical engineering from the University of Texas at El Paso. He is currently a manufacturing engineering supervisor at HP's San Diego division. He was born in Newark, New Jersey and served four years in the U.S. Air force. Bob enjoys listening to Christian music, is an avid reader, and leads the singing at his church. He lives in Escondido, California, is married, and has two children.



David C. Tribolet

Dave Tribolet designed the pen-change mechanism and X-axis mechanics for the 7470A. With HP since 1979, he is presently an R&D project leader. Dave was born in Tucson, Arizona, and received a BSME degree from the University of Arizona in 1978. Further studies at Stanford University have earned him the MSME degree in 1979 and the MSEE degree in 1982. Living in San Diego, California, Dave teaches a machine design course at the University of California at San Diego, and likes basketball and sailing.

Chuong C. Ta

Chuong Ta joined HP in 1979 and worked on the X-axis drive, paper loading, and encoder portions of the 7470A. A native of Hanoi, Vietnam, he attended the National Technical Center in Vietnam, earning a BSME degree in 1974. Chuong also received the BSME degree from the University of Minnesota in 1979, and recently was awarded an HP Fellowship to complete his studies for an MS degree. He likes swimming and music, is married, has one daughter, and lives in Escondido, California.

Richard M. Kemplin

Dick Kemplin has been with HP since 1954 and presently is a development engineer at HP's San Diego division. His contributions have resulted in six patents related to mechanisms and two previous HP Journal articles. Dick has an AA degree from John Muir College, Pasadena, California, awarded in 1951, and served two years in the U.S. Army. Born in Glendale, California, he now lives in Poway, California. Dick is married, has four children, and is interested in art and building detailed scale models.