HEWLETT-PACKARD JOURNAL

A New Family of Intelligent Multi-Color X-Y Plotters

These fast, precise, programmable plotters draw report-quality four-color plots. Features include dashed-line fonts, several built-in character fonts, user-defined characters, and symbol plotting.

by Lawrence G. Brunetti

GRAPHIC PEN PLOTTERS provide a permanent, graphical representation of collections of numbers. The numbers may be derived from financial and statistical data bases, test and measurement system outputs, or computational results. The idea is similar in all cases—turn the numbers into graphic representations that promote the human visual data reduction process.

Models 9872A and 7221A X-Y Plotters (see Figs. 1 and 2) are designed to perform this function with unprecedented facility. These programmable microprocessor-based A3-size (11×17 in) plotters produce high-quality plots in up to four colors. Basically identical, the two plotters differ in their input/output interfaces and in some built-in functions.

The design of a new generation of X-Y plotters presented opportunities to try out exciting new technology. But technology must be transformed into product features that benefit the user. Therefore, the objectives for the new plotters included such user benefits as improved line quality, mechanical reliability, and low cost of ownership.

Line Quality

Line quality starts at the prime mover. Servomechanisms are the traditional means of reducing the effects of imperfect mechanisms and motors. The 9872A/7221A approach is to start with an inherently linear step motor and an essentially constant torque curve. The coupling between motor shaft and pen tip is a stiff, deadband-free mechanism instead of the traditional servo loop.

The mark that a pen plotter leaves on the paper is a permanent record of how the mechanism moved the pen from point A to point B. An S-shaped anomaly of 0.1 mm peak-to-peak amplitude spread out over a 100 mm vector has zero visual impact, but a series of 0.1-mm sinusoidal anomalies at a wavelength of 1 mm will cause great concern for the health of the mechanism. Line width changes or modulation can be caused by the pen bouncing at the beginning of a vector, or by a pen tip that can't deliver sufficient ink

at the maximum slewing velocity. The 9872A/7221A writing system delivers high-performance vector

Cover: *Model 9872A X-Y Plotter is the HP-IB (IEEE 488) version of a new pair of microprocessor-based programmable four-color plotters. The other version, Model 7221A has a binary-coded RS232C interface.*
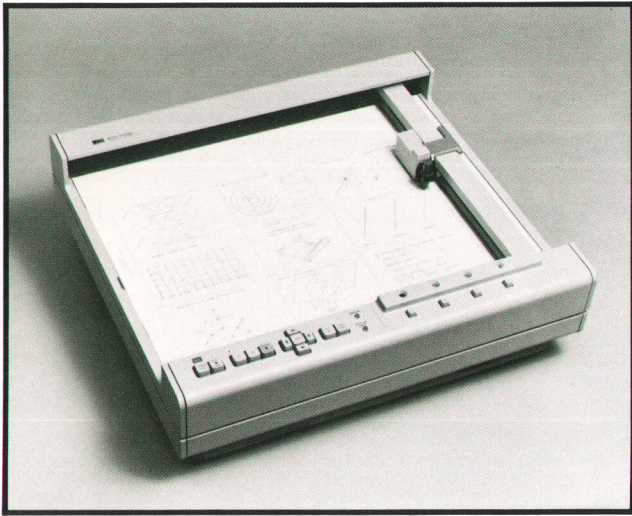
In this Issue:

Fig. 1. *HP Interface Bus version of the new four-color X-Y plotter, Model 9872A, is compatible with IEEE Standard 488. It has five built-in character sets, point digitizing capability, and internal self-test.*

plotting at line quality exceeding older designs by 2:1. For extreme cases, near-perfect line quality can be achieved by use of a velocity command that gives the user a choice of maximum slewing speed or a 2:1 reduction in acceleration.

Mechanical Reliability

A mechanism starts to wear out the moment it begins to move. Our job was not to discover when the design would fail, but to design a mechanism that would make a life test boring. One example is the X and Y travel guide mechanisms. Loaded linear ball bearings on hardened steel shafts have demonstrated an actual life exceeding the objective of 100 miles of travel by 4 to 5 times.

A pen plotter draws vectors. In some applications, the vectors most often drawn result in characters. As the character drawing speed is increased in new plotters, the user feels more compelled to use that speed. This increase in use of the character drawing capability has a large impact on the perceived reliability of pen lift mechanisms. Traditional mechanisms designed to pick up the pen at the end of the final vector in a curve don't last long when a lot of text is drawn. By paying proper attention to the fundamental pen lifting mechanism, an order-of-magnitude increase in pen lift life was achieved. By concentrating on the design of mechanisms that would work inherently, these kinds of improvements in life were realized throughout the product.

Cost of Ownership

Cost of ownership has many components: initial purchase price, consumables (paper, pens), down/up time ratio (which includes mechanical reliability),

repair cost, service life, ease of use (training required), and many other factors.

Troubleshooting a product that has difficult access for test instrumentation is frustrating and time-consuming. The 9872A/7221A solution is to first make access easy, and then to allow full operation of the product while probing for the problem. The modular concept and subassembly repair are retained and are enhanced by the self-test/diagnostic system built into the plotter. Self test is implemented at two levels. An external confidence test switch can be used to exercise most of the circuitry and mechanics, and an internal self-diagnostic system provides a comprehensive troubleshooting aid that quickly isolates problems to a particular printed circuit assembly and in some cases to a particular component.

The Need for Intelligence

A plotter is always part of a system. The plotter may be simple—having the ability to understand only the minimum set of instructions: MOVE, PEN UP, PEN DOWN. Here, the burden is placed on the controller for providing high-level graphic capabilities, and the I/O channel carries messages that describe every move the plotter makes. Alternatively, the controller may be kept busy doing other things, or the communication channel may be slow. The plotter may then be given computational and decision-making power that exceeds that of the controller. The question becomes one of the division of intelligence, and must be answered early in the game.

Two factors influence the division of intelligence. The first is the capability of the controller. In a computer system, where the plotter is supported by a
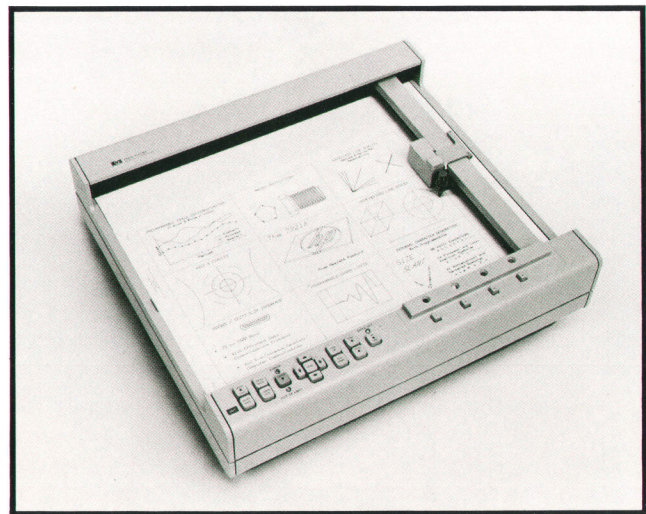

Fig. 2. *Remote terminal four-color X-Y plotter, Model 7221A, has an RS232C interface. Emphasis is on maintaining plotting speed independent of the interface at low baud rates. Special instructions help reduce the volume of traffic on the communications link.*
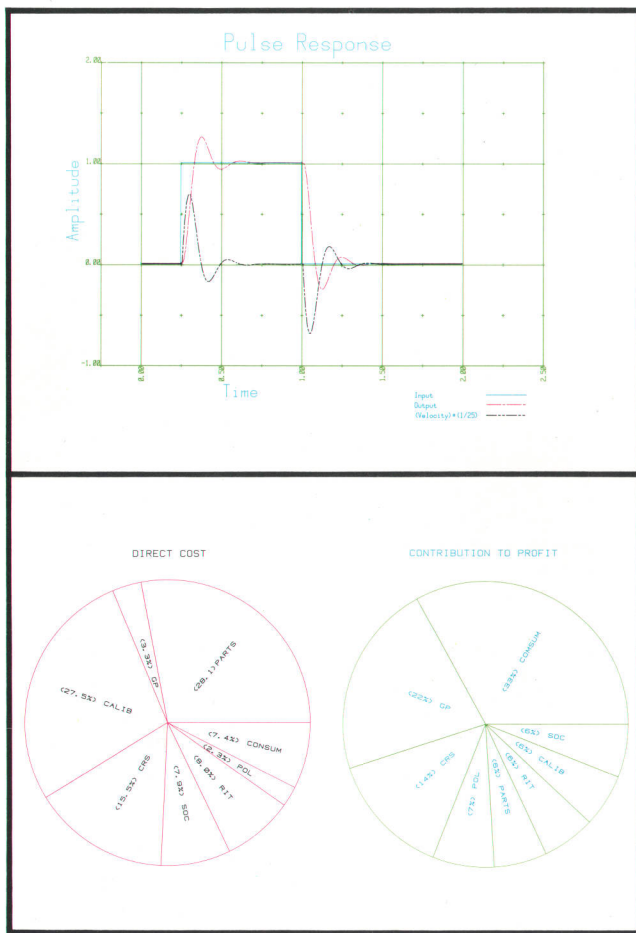
Fig. 3. *Examples of four-color business and engineering plots that are easily programmed on the 9872A and 7221A X-Y Plotters.*

software driver, the tendency is to minimize the plotter intelligence: keep it simple. This results in a large software driver and a correspondingly high volume of traffic on the I/O channel. In systems where much of the peripheral support is in the form of read-only memory (ROM), the tendency is the opposite. Plotter intelligence is emphasized to minimize special plotter ROMs in the controller, and in some cases the plotter is virtually self-supporting.

The second factor is the speed of the I/O channel. The HP interface bus, or HP-IB (IEEE Standard 488), is virtually instantaneous to a plotter, although plotter communication may interfere with other I/O activity. Interface standard RS232C may be looked at as being subdivided into two categories: hardwired and common carrier. Hardwired, the data rate at 2400 baud is high enough that the communication time is not a major consideration. On the other hand, common carrier data rates on unconditioned lines are typically only 110 to 300 baud, and the cost of telephone time may discourage plotting. Ironically, on the other end of a timeshare line may be a highly capable computer whose output must be squeezed through a tiny 110-

baud aperture.

A Family of Plotters

Two versions of the basic mechanism and operating system were established, the major difference being the I/O channel and the firmware capability needed to operate in these two different environments.

Model 9872A interfaces with the HP Interface Bus, or HP-IB (IEEE 488). The plotter intelligence is accessed via a mnemonic graphics language called HPGL. A mnemonic language was chosen so that controllers that do not support the 9872A with a high-level driver can be easily programmed to use the graphic functions built into the plotter.

The second version, Model 7221A, has an RS232C interface. Heavy emphasis is placed on maintaining plotting speed independent of the interface at low baud rates. The interface language is binary coded, and special instructions can be used to reduce the volume of individual vector commands.

Certain graphic functions are common to both plotters. Character generation, programmable line types made up of dashes and dots, programmable velocity for high-quality plots on various media, and centered character plotting for curve differentiation are a few examples.

Repetitive and common graphic routines such as circles, axes, translations, and rotations are a few capabilities that fall into a grey area. In the 9872A, these are left to the programmer as subroutines. In the 7221A, which is subject to slow communications at 110 and 300 baud, the traffic is reduced significantly by a plotter-resident arc generator and macroinstructions. The arc instruction reduces communication to the information required to specify an arc, rather than
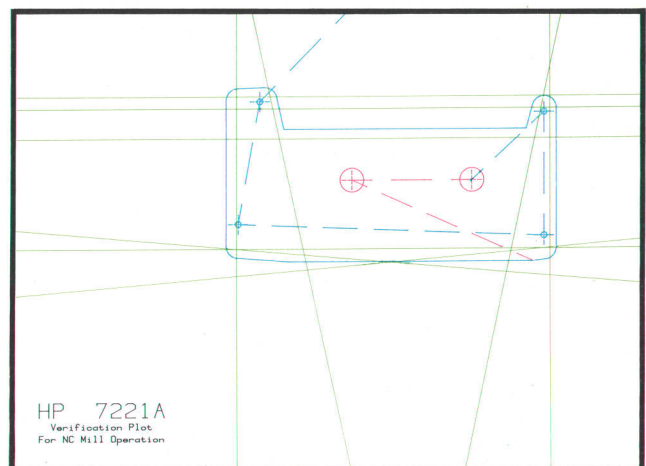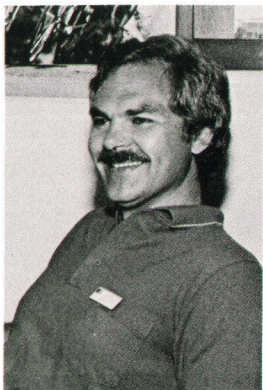

Fig. 4. *Model 7221A significantly reduces the time required for numerical control verification plotting. Macroinstructions and single-command arc and circle generation are important 7221A features in this type of application.*

4

Lawrence G. Brunetti
With HP since 1969, Larry Brunetti has served as project leader and group leader for oscillographic recorders, as a product planner, and as section manager for digital plotters. He was born in Reno, Nevada and attended the University of Nevada, graduating in 1959 with a BSEE degree. During the next ten years he designed television receivers and nuclear instrumentation, and earned his MSEE degree from the University of California at Berkeley in 1964. He's married, has three children, and lives in Escondido, California, where he serves on the city bikeways committee and as chairman of the local Boy Scouts troop. He plays organ and guitar, and enjoys woodworking, cooking, and of course, bicycling.

each chord. Macroinstructions can be stored in the plotter and executed with a two-byte message. The storage space also acts as a buffer for all graphic commands. The buffering of vector end points while a macroinstruction is being plotted keeps the pen moving even at an input rate of 110 baud.

Acknowledgments

SPECIFICATIONS
HP Models 9872A and 7221A X-Y Plotters

PLOTTING AREA
Y AXIS: 280 mm (11 in)
X AXIS: 400 mm (15.75 in)
Accommodates up to ISO A3 and 280 × 432 mm (11 × 17 in) chart paper.

PLOTTING ACCURACY
±0.2% of deflection ±0.2 mm (0.008 in) [includes linearity and repeatability and assumes the plotter has been "zeroed" exactly to the lower left (0.0) coordinates].

REPEATABILITY
FOR A GIVEN PEN: 0.10 mm (0.004 in)
PEN-TO-PEN: 0.20 mm (0.008 in)

ADDRESSABLE RESOLUTION: Smallest addressable move: 0.025 mm (0.001 in)

SPEED
MAXIMUM: 360 mm/s (14 in/s) in each axis, 509 mm/s (20 in/s) on 45° angle.
PROGRAMMABLE: pen speed may be adjusted to any one of 36 speeds from 10 mm/s (0.4 in/s) to 360 mm/s (14 in/s) in 10-mm/s (0.4 in/s) increments under program control.

VECTOR LENGTH: No limit—any length vector within the plotter's mechanical limits will be plotted to within the previously mentioned accuracy.

CHARACTER PLOTTING SPEED: 3 characters/s typically for 2.5-mm (0.1-in) characters.

OFFSCALE PLOTTING: When offscale data is received by the plotter, the plotter will automatically calculate the mechanical limit intercept of that vector and proceed to that point. As additional offscale data are received, the plotter will monitor the location of these data and resume plotting, once onscale data is received, by again calculating the new mechanical limit intercept and plotting from that limit to the on-scale data point. Plotting accuracy and repeatability specifications are preserved.

PEN CONTROL: Local control by front-panel switches or remote control by program commands; capable of >20 operations/s.

POWER REQUIREMENTS
SOURCE: 100/120/220/240V −10%, +5%
FREQUENCY: 48-66 Hz

ENVIRONMENTAL RANGE
TEMPERATURE: 0°C to 55°C
RELATIVE HUMIDITY: 5% to 95% (below 40°C)

SIZE/WEIGHT
HEIGHT: 189 mm (7.5 in)
WIDTH: 497 cm (19.5 in)
DEPTH: 455 mm (18 in)
NET WEIGHT: 18.2 kg (40 lb)
SHIPPING WEIGHT: 25.4 kg (56 lb)
CUBE: 0.21 m³ (7.4 ft³)

PRICES IN U.S.A. 9872A, $4200. 7221A, $4600.

MANUFACTURING DIVISION: SAN DIEGO DIVISION
16399 West Bernardo Drive
San Diego, California 92127 U.S.A.

Easy-to-Use Interface Language Controls HP-IB Plotter

by Thomas H. Daniels and Larry W. Hennessee

MODEL 9872A X-Y PLOTTER is designed to interface to controllers via the Hewlett-Packard Interface Bus (IEEE 488). This bus provides for the transfer of ASCII-coded data between controllers and instruments.

Fig. 1 is a block diagram of the 9872A Plotter. The operating system exists in 5K 16-bit words of firmware stored in read-only memory (ROM). It is executed by the HP Calculator Products Division's binary processor chip (BPC) microprocessor.[1]. The

system further requires 256 16-bit words of random-access memory (RAM) for stack operations, scratchpad, and instruction and parameter storage.

Upon power-up, an internal switch is first tested to determine whether the plotter is to run in its normal mode or if its internal self-test is to be executed. Assuming that the normal mode has been selected, the ordinary and expected initialization procedures are executed as indicated in Fig. 2. Upon completing this sequence, the operating system falls into its final
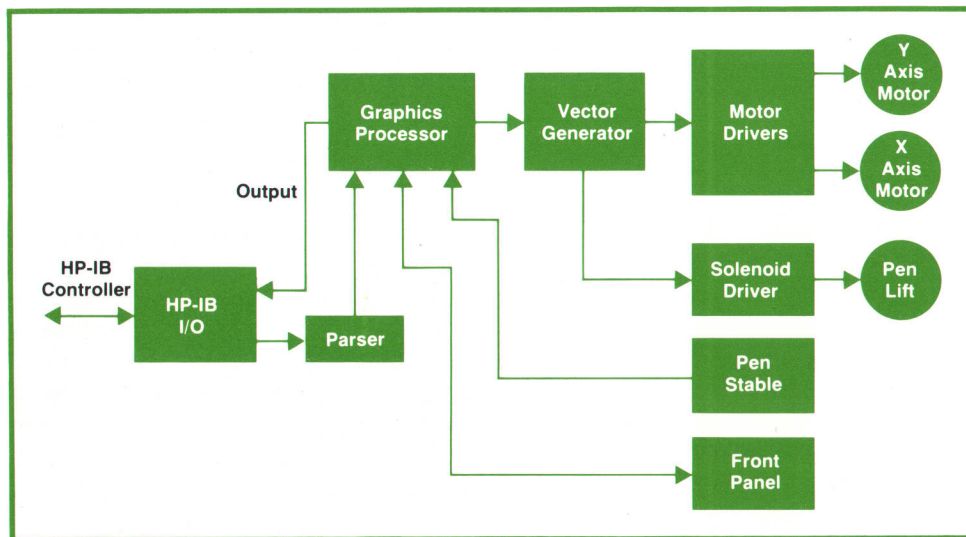
Fig. 1. *Block diagram of Model 9872A X-Y Plotter.*

execution state, a small executive loop in which it polls its I/O interface and its own front panel for requests.

Front-panel requests are always in the form of one or more pushbuttons' being pressed by the operator, e.g., "go to lower left" or "select pen 2". By means of 16 pushbuttons, the operator can select or put away any of four pens, move the pen around the full surface of the platen at two speeds, go to or set either the lower left or upper right scaling points, enter a digitized point, turn chart hold off and on for paper loading, raise or lower the pen, or completely re-initialize the plotter.

All functions that can be commanded from the front panel can also be invoked by a program via the I/O interface, except for turning chart hold on or off and entering a digitized point.

Program inputs are in the form of commands sent over the I/O from the controller, e.g., a calculator or computer. The command format is a sequence of ASCII characters. Each command begins with a two-alpha-character instruction code followed by any necessary parameters, and ends with a terminator character. Multiple parameters are separated by commas. The instruction characters can be upper or lower case, and the terminator is either a semicolon or a line-feed.

After the plotter is initialized at power-up, or has received a command terminator, the I/O firmware combines the next two input characters to form an instruction. This instruction is compared to all entries in the plotter's internal instruction list. Once a match is detected, control is transferred to the firmware associated with this instruction. The instruction code then instructs the I/O firmware as to the form of its parameters. The parameter types are as follows:

- Integer: optional sign, integers between -32768 and $+32767$, and no decimal point
- Decimal: optional sign, numbers between -127.999 and $+127.999$, and an optional decimal point
- Printing characters: any character to be drawn by the plotter while in label mode.

When the plotter receives X-Y coordinates that are too large to be handled within the word size of the processor, the plotter enters a lost mode and blinks the front-panel out-of-bounds light. While in lost mode every command that would otherwise cause pen motion is ignored until a pen motion command within the processor's range is received.

If a coordinate pair to be plotted is within the processor's range but off the platen, a clipping function causes the pen to move from its current position on the platen toward this next point, and stop at the edge of the platen. Moving from a point outside the platen back onto the platen, a pen-up move is made to the point on the edge of the platen where the incoming line would intersect the edge and then the remainder of the line is drawn in from the edge to the point. These are special cases of the plotter's general clipping function: any rectangle can be mapped onto the platen under program control to restrict pen motion to be within the defined area. This makes it possible to protect the area outside the rectangle. When the current point to be plotted lies outside the clipping area the front-panel out-of-bounds light is turned on.

Every millisecond an interrupt occurs within the plotter. The interrupt service routine's primary function is to output numbers to the hardware interpolator that drives the X and Y-axis motors (see article, page 13). A velocity profiling algorithm, upon receipt of a move command from either the I/O system or the front panel, accelerates the arm from rest to some slew velocity and then begins to decelerate the arm at the proper distance from its destination, stopping it at the
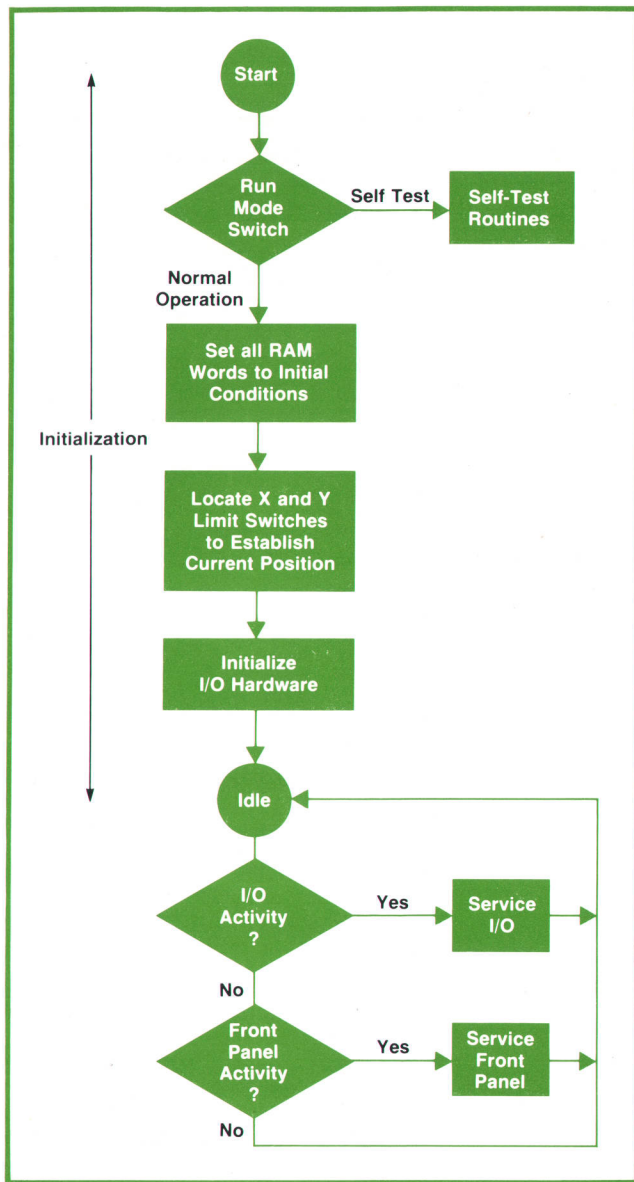
6

Fig. 2. *9872A Plotter is controlled by an HP microprocessor. The operating system is stored in read-only memory. After initialization, the operating system settles into a small executive loop.*

requested end point. The slew velocity while the pen is down is programmable via the I/O system. Pen-up moves are always made at maximum speed. Should some velocity be requested other than the default full velocity, the plotter assumes the user is more interested in line quality than in speed, and the acceleration and deceleration are automatically halved.

Besides accelerating, slewing, and decelerating the motors by computing numbers for the interpolator, the interrupt routine has three minor tasks: to control any blinking of the front panel lights, debounce the front panel switches, and lift the pen after it has been motionless for approximately one minute. The au-

tomatic pen lift is to prevent ink bleeding. This is a hardware change of pen state only; the controller still considers the pen to be down, and before any subsequent X or Y motion, the pen will be set down automatically by the plotter firmware.

Self-Test

Approximately 10% of the ROM space was set aside to allow the instrument to be self-tested. Self-test consists of a series of tests used to detect failure in the electronic components or aid in the adjustment of the pen drive system (see Fig. 3).

Self-test has an automatic and an interactive phase. The automatic part of the test consists of exercising the CPU and interrupt system, checking sums on all ROMs, RAM testing, and I/O testing. The interactive portion tests I/O address switches, front-panel switches, and LEDs. Tests to exercise the pen drive system are also provided to move the arm at specified angles for electronic compensation adjustments.

The self test is controlled by a test advance pushbutton and an internal bank of rocker switches, and is monitored by an internal LED (light-emitting diode) display. The operator sets the desired test number into rocker switches and then presses the test advance pushbutton. Success or failure is indicated by an octal code (0 through 77) output to the LED display. The cause of any failure is established at least to the board level and in some cases to the component level.

In addition to these internal instrument self-tests, a user confidence level test has been provided. When the operator sets a rear-panel switch, the instrument goes through its automatic electronic self-test, then waits for the rear-panel switch to be reset. When the operator resets the switch, the plotter does a power-up initialization.

Interface Language

Since the 9872A was an entirely new design, it represented an opportunity to design an interface language that would be easy for the user to understand and apply.

The 9872A language is called HPGL, for Hewlett-Packard Graphic Language. With HPGL the user can access plotter capabilities that may not be present in the controller's plotter ROM or software, such as velocity control (VS), user-defined characters (UC), slant characters (SL), and so on. The plotter can be driven by any controller that can talk to the HP-IB. Examples are the HP 9831A, 9830B, and 9825A Desktop Computers.

In the 9872A, HPGL has thirty-eight different commands, each represented by two ASCII characters (Fig. 4). The letters in most cases represent the abbreviation of the command itself: PA means plot abso-
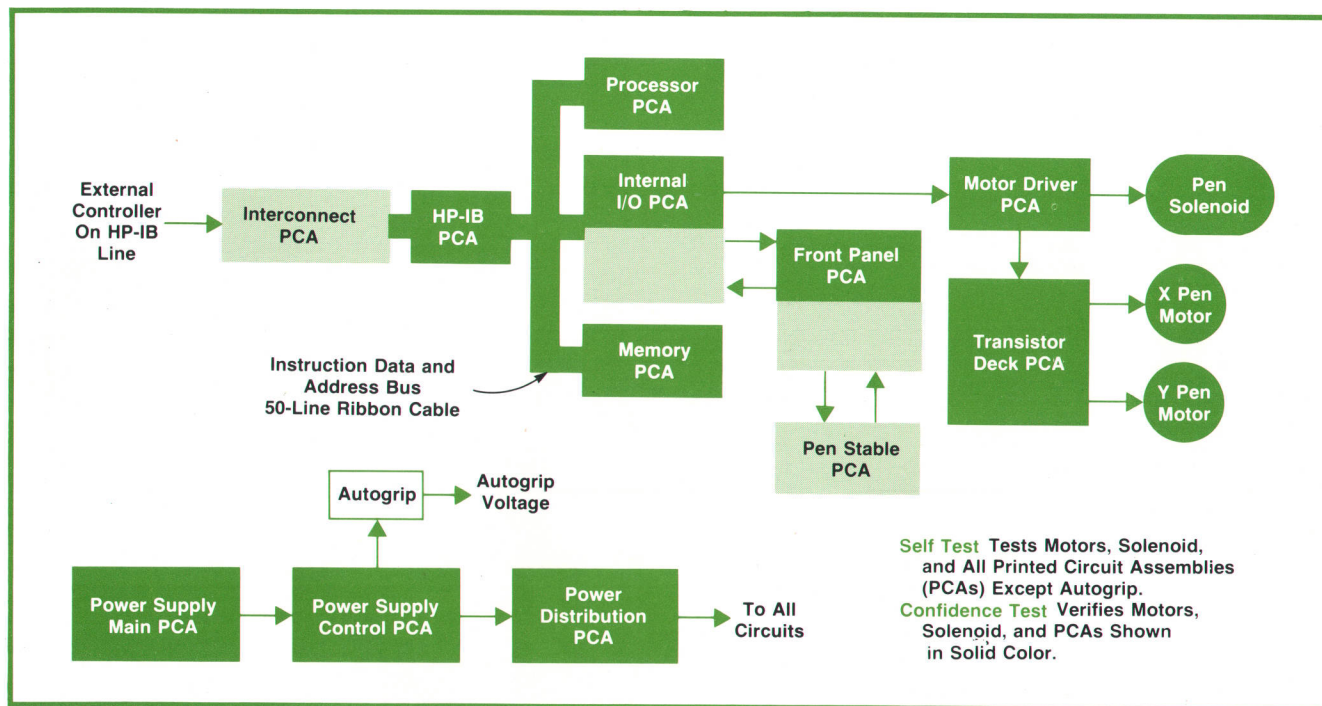
Fig. 3. *Self-test is built into both the 9872A and the 7221A Plotters. The complete self-test identifies the faulty printed circuit board or component. A less thorough confidence test is also provided.*

Fig. 4. *HPGL is a high-level graphic language used for controlling the 9872A Plotter. The plotter can be driven by any controller that can talk to the HP interface bus.*

lute, PD means pen down, SP means select pen, and so on.

When a command requires a numeric parameter in addition to the two-letter mnemonic, the numeric parameter is also sent in ASCII form. For instance, the command to select pen number four is: SP4;.

Commands are delimited with semicolons and can be strung together, such as: PD; SP1; SP2; SP3; PU;.

The plotter's plotting area is divided into plotter units, each of which is equal to 0.025 mm. To cause the plotter's pen to move to a certain position, HPGL uses PA or PR with coordinate pairs sent in plotter units. For instance, to move the plotter to the coordinate 100 mm, 200 mm, the HPGL ASCII string sent over the I/O would be PA4000,8000;. Coordinate pairs can also be nested within the PA command, such as PA0,0,4000,8000,5000,6000;.

The plotter can act as either a talker or a listener on the bus. When it is receiving plot data it is a listener, but it can also output data to the controller. This data can be error messages, status messages, current position, digitized position, and so on. The commands used to do this are OE, OS, OC, and OD, respectively.

To further illustrate how HPGL works, let's examine some examples of how a typical bus controller, such as the HP 9830B, would use HPGL to run the 9872A. The 9830B is programmed in BASIC and uses a CMD statement to access the HP-IB. Other controllers use WRITE or PRINT statements to do the same thing.

A 9830B BASIC program line that would cause the

9872A to select pen four and plot a square with the origin at 0,0 and with 10-centimetre sides, would look like:

```
10 CMD"?U%","SP4;PU;
   PA0,0;PD;PA0,4000,
   4000,4000,4000,0,
   0,0;"
```

The first part of the statement, "?U%", sets up the 9830B as a talker and the plotter as a listener. The second part of the statement sends HPGL code to the plotter.

A program that would output X and Y variable values to the plotter would look like:

```
10 CMD"?U%"
20 OUTPUT (13,30) "PA",X,Y
30 FORMAT F6.0,",",F6.0
```

where line 20 is an output statement that is formatted by line 30.

These examples illustrate that any controller that can send ASCII characters to the HP-IB can control the 9872A.
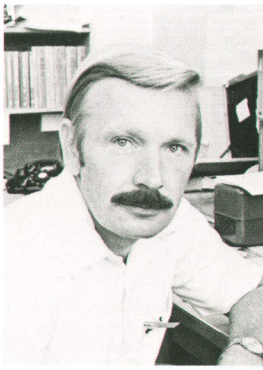
Acknowledgments

Larry W. Hennessee
Larry Hennessee developed much of the firmware for the 9872A and 7221A Plotters. A native of the state of Ohio, Larry received his BSEE degree in 1963 from Case Institute of Technology. After five years as a programmer for real-time inertial navigation systems, he joined HP in 1968 and developed some of HP's first software for computer/instrumentation systems. Now designing firmware with HP's San Diego Division, Larry lives in Rancho Bernardo, California. He's married and has two sons who are active in organized sports, so Larry is, too. He also enjoys swimming and reading.

Thomas H. Daniels
Tom Daniels was project manager for the 9872A Plotter. He's been with HP since 1963, serving as a design engineer and as group leader for 7040-Series X-Y Recorders. A native of Los Angeles, he received his BSEE degree in 1963 from Northrop Institute of Technology. He's married, has two children, and lives in Escondido, California. His favorite leisure activities are golf, fishing, and camping.

Reference
1. W.D. Eads and D.S. Maitland, "High-Performance NMOS LSI Processor," Hewlett-Packard Journal, June 1976.

Remote Terminal Plotter Offers Simple Programming and Efficient Communications

by David A. Bones and Marvin L. Patterson

THE BANDWIDTH of the interface channel has a direct impact on the design of a peripheral device. Comparing the 9872A Plotter described in the preceding article with the 7221A Remote Terminal Plotter makes this clear.

In the case of the 9872A Plotter, the HP-IB interface provides a relatively high bandwidth compared to the data rates required for vector graphics. This allows the use of a high-level mnemonic interface language, HPGL, that transfers graphic data in an easily read-able form. On the other hand, a timeshare user attempting to plot program output through a ten-character-per-second serial digital interface would be seriously hindered by the data communication time required for such a high-level interface language. For instance, a single absolute move such as PA2000, 3000 can take over a second to transmit at ten characters per second. The plotter is capable of plotting at a much higher rate, so the graphic system quickly becomes interface limited.
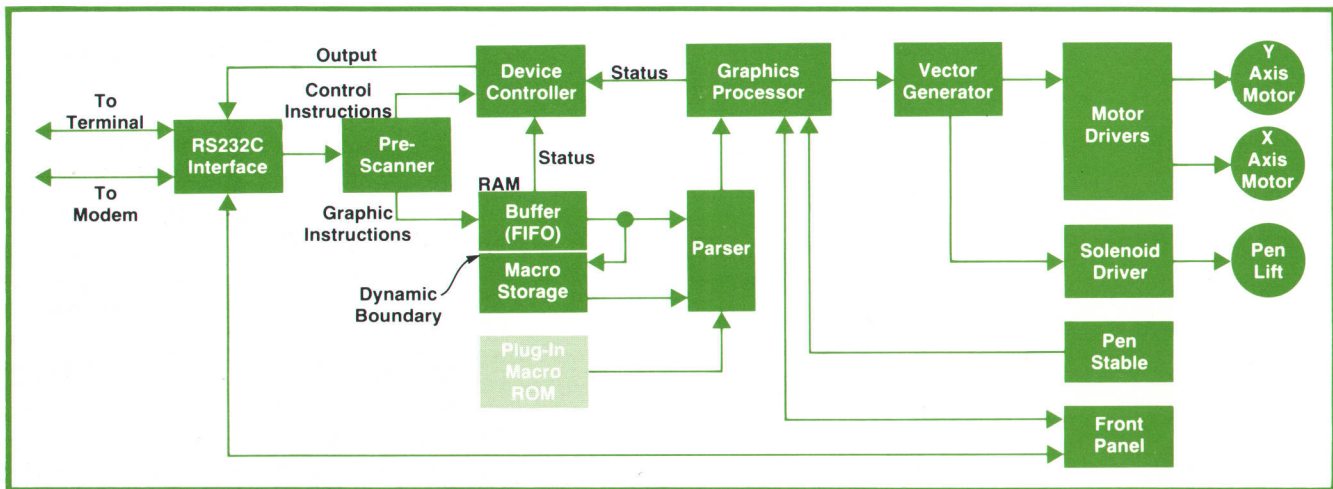
Fig. 1. *Block diagram of Model 7221A Remote Terminal X-Y Plotter.*

The data communications environment also impacts the features that are useful to the user. For instance, the 9872A is capable of window plotting, that is, clipping incoming plot data at a predefined boundary. In the serial interface environment, this would imply the transmission of large amounts of data that simply are not plotted. This would be both time consuming and expensive to the timeshare user. Instead, software is usually provided in the timeshared computer to provide this clipping function. Data points outside the clipping window are suppressed and only those points that contribute to the final graphics are transmitted.

On the other hand, certain graphic features such as arcs and circles require the transmission of large amounts of redundant data. A circle containing 36 chords typically takes 144 characters of transmitted data to accomplish on a remote plotter, whereas the actual data required to define the circle is on the order of only eight characters. Therefore, a useful feature of the 7221A that saves large amounts of data transmission time is an arc-generation algorithm within the plotter.

The 7221A Remote Terminal Plotter essentially redirects the microprocessing power resident in the 9872A to optimize performance with a band-limited serial digital interface. An efficient binary interface language is used to minimize the number of characters necessary for vector plotting. Advanced graphic features have been included such as arc generation, programmable macroinstructions, definable dashed line generation, and internal generation of six character fonts. These features minimize the need for redundant data transmission, thus saving the user both time and timeshare costs. An 1150-byte buffer (expandable to 3198 bytes) stores incoming graphic plot data.

Fig. 1 is a block diagram of the 7221A Remote Ter-

minal Plotter.

Binary Data Format

The binary format used in the 7221A accomplishes several objectives. First, it provides data communication efficiency by minimizing the number of characters necessary to specify data points. X-Y pairs can be sent with one, two three, four, or five characters, with each character carrying a minimum of four and usually six bits of information. Leading zeros can be suppressed so the data format expands or contracts to accommodate the largest component. Most frequently used instructions are encoded as single ASCII characters.

Second, the data format is self-delimiting so that long strings of X-Y data can be transmitted without the need to insert extra characters to show where one data point ends and another begins. Finally, the data format does not include the 32 ANSI-standard control characters commonly used in timeshare environments to control peripheral devices. This eliminates many of the problems encountered in the past with the transmission of binary graphic data over a timeshare communication network designed to operate printing terminals.

As shown in Fig. 2, the instruction format provides for three different command levels. First, peripheral control instructions are coded as ANSI-standard three-character escape code sequences. These instructions are executed immediately when received by the 7221A. First-order graphic instructions are encoded as a single printing ASCII character. Second-order graphic commands consist of a sequence of two printing characters, always beginning with a ~. Both types of graphic commands are always routed to an internal data buffer and executed on a first-in-first-out basis. This command format provides the flexibility needed for the existing 41 instruc-

BINARY CODING

Device Control Commands	0011011
	0101110
	*nnnnn
First Order Graphic Commands	111nnnn
Second Order Graphic Commands	1111110
	*nnnnn
Numeric Parameter	
0 to 63	*nnnnn
Absolute Graphic Parameter	
0 to 15	110nnnn
0 to 1024	110nnnn
	*nnnnnn
0 to 32767	110 - nnn
	*nnnnnn
	*nnnnnn
Absolute XY Parameter	
0 to 3	110xxyy
0 to 31	110xxxx
	*xyyyyy
0 to 255	110xxxx
	*xxxxxy
	*yyyyyy
0 to 2047	110xxxx
	*xxxxxx
	*xyyyyy
	*yyyyyy
0 to 16383	110xxxx
	*xxxxxx
	*xxxxxy
	*yyyyyy
	*yyyyyy
Incremental X Parameter	
−16 to 15	10xxxxx
−512 to 511	10xxxxx
	10xxxxx
−16384 to 16383	10xxxxx
	10xxxxx
	10xxxxx

Incremental Y Parameter
similar to X axis except for leading two bits, i.e;
−16 to 15   01yyyyy
All incremental XY data points consist of one to three bytes of X data followed by one to three bytes of Y data.

Angle Parameters

Byte	Coding	Significance of Bits (Degrees)			
1	110nnnn	180	90	45	22.5
2	*nnnnn	11.25 5.63	2.81	1.40	0.703 0.352
3	*nnnnn	0.176 0.088	0.044	0.022	0.011 0.006

One byte yields resolution to 22.5 degrees.
Two bytes yield resolution to 0.352 degrees.
Three bytes yield resolution to 0.006 degrees.
All angles are positive. Zero degrees is at the three o'clock position.

* means bit 7 is the complement of bit 6
\- means bit not used

Fig. 2. *7221A instruction formats. Coding is binary. The interface conforms to standard RS232C.*

ciently. In previous plotters four characters of data typically had to be transmitted for each stroke in each letter that appeared on a plot. Thus the letter M required the transmission of about 20 characters each time it was drawn. With its internal character generator, the 7221A requires only one character for each letter drawn. This makes labeling of graphics much faster and less expensive.

An arc generator in the plotter accepts the radius, start angle, and stop angle of an arc and then generates a sequence of pen motions that approximate the specified arc with straight chords. If a circle is desired, only the radius needs to be specified. If a radius has already been specified in a previous command, only the single character command for the arc must be sent to generate another circle of the same radius. The user can trade cosmetics of the approximated arc for faster execution time by specifying the tolerance of the arc generation algorithm. This sets the maximum distance between the straight line chords and the theoretical arc.

Often a feature in a plot is repeated again and again. The data necessary to specify this feature typically has to be sent each time it is drawn. The 7221A has the ability to store macroinstructions that make this redundant transmission of data unnecessary. Macroinstructions are analogous to user-definable keys on a programmable calculator. Any sequence of valid graphic instructions and data can be stored in mem-

---

DEVICE CONTROL COMMANDS

I/O Control Group	**Output Group**
Plotter On	Output Identification
Plotter Off	Output Status
Set Handshake Mode	Output Buffer Size
(Dependent)	Output Current Buffer Space
Set Handshake Mode	Output Graphic Limits
(Independent)	Output Current Position
Set Output Mode	Output Error
Output Abort	Output Digitized Point
Buffer Abort	

GRAPHIC COMMANDS

Setup Group	**Label Group**
Initialize	Label Mode On
Set Grid Size	Label Size
Graph Limits	Label Font
Velocity Select	Label Slant
Arc Tolerance	Set String Terminator
Plot Group	**Macroinstruction Group**
Move	Macroinstruction Define
Draw	Macroinstruction Terminate
Incremental Move	Macroinstruction Invoke
Incremental Draw	Automatic Macroinstruction
Arc Clockwise	
Arc Counterclockwise	
Rotate	
Rotate at Last Angle	
Pen Select	
Dashed Lines, Fixed	
Dashed Lines, Variable	
NOP	

Fig. 3. *7221A Plotter instructions.*

tions listed in Fig. 3 and for future expansion of the instruction set.

Firmware Features

Several new features in the 7221A reduce the number of characters needed to generate a typical plot. First, an internal character generator similar to that of the 9872A allows plots to be labeled effi-

ory within the plotter and defined as a macroinstruction numbered 0 through 63. A macroinstruction thus defined can then be invoked repeatedly in different locations on the plotter by a two-character command.

Dashed lines are often used in graphics to differentiate one type of curve from another or to signify hidden lines or centerlines. These have always been costly and time consuming in the timeshare environment. The endpoints of each dash and space had to be transmitted at a cost of four characters per endpoint to execute the dashed line. A dashed line generator is included in the 7221A that eliminates this burden on the communication link. The user can define any dashed line font with up to sixteen different lengths of dashes and spaces. The length of the repeating pattern can also be specified. Typically this specification will be stored in a macroinstruction so that it can be reinvoked whenever necessary.

A user's application sometimes includes a large number of commonly used graphic features such as dashed line fonts, hole patterns, or other special purpose graphic symbols. In this case, it may be advantageous to have optional plug-in ROMs programmed with macroinstructions that create these features. The 7221A is designed to accept macroinstructions that are permanently stored in an optional plug-in module. This allows the use of special graphics custom tailored to an application without having to define them through the communication link.

Operational Modes

The 7221A is designed to be inserted in the serial communication link between the host computer or modem and a terminal. When installed, the cable from the modem or host computer and the terminal are both routed to connectors on the plotter. Three operating modes allow the plotter to receive data from and send data to the host computer, receive data from and send data to the terminal, and pass data between the host computer and the terminal.

In the LOCAL mode the plotter communicates directly with the terminal. This can be done either with the host computer connected or off-line. In this mode the operator can label plots created on-line without using further computer resources. If an HP terminal that has magnetic tape readers is used, plots that have been previously stored on tape can be duplicated on the 7221A. Finally, the operator can interrogate the plotter to establish the plotter's status, buffer size, or error history.

A STANDBY mode is provided so the plotter can be rendered passive during the transmission of binary data between the terminal and the host computer. This mode is also used when plot data is being stored on magnetic tape by the terminal.

Normally the plotter is left in the ON-LINE mode so it will intercept plot data when it is sent. When this mode is entered, the plotter is programmed to an OFF state. A PLOTTER ON command then causes the plotter to interpret incoming data from the host computer as plotter data. When a PLOTTER OFF command is received the plotter returns to a passive state and sends
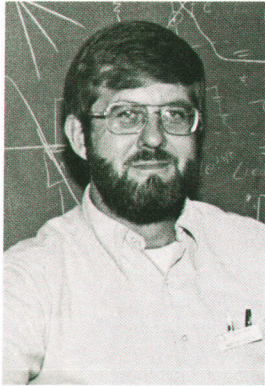
Marvin L. Patterson

Marv Patterson was project manager for the drive system of the 9872A plotter and for development of the 7221A Plotter. He earned his BSEE and MSEE degrees at the University of Washington in 1963 and 1970, respectively. Before coming to HP in 1973, he was a project engineer and section head for microwave antenna and telemetry system development. He's authored papers on microstep control and magazine articles on active filter design. Born in Ontairio, Oregon, Marv is married, has three children, and lives in Ramona, California. He's been a Little League coach and is active in the YMCA. He enjoys canoeing and skiing, but his real passion is sport flying in his 1948 Stinson.

David A. Bones

Dave Bones received his BSEE degree from California Polytechnic University in 1973 and joined HP's San Diego Division the same year. He's been involved with investigations of processor system designs and firmware techniques, and was the developer of much of the 7221A firmware. Born in St. Louis, Missouri, Dave is single and lives in Escondido, California. He's a rock climber, a backpacker, and an enthusiastic user of one of the San Diego area's major attractions—the beach.

incoming data on to the terminal. In this condition the plotter is sensitive only to another PLOTTER ON escape code sequence.

Interface Information

The 7221A Plotter uses the RS232C serial interface and is compatible with the European CCITT V.24 standard interface. Baud rates of 75, 110, 150, 200, 300, 600, 1200, and 2400 can be selected. The plotter can be set to check for even or odd parity when receiving plotter data or it can be set to ignore parity. When the plotter is OFF it simply passes data between the terminal and host without checking or generating parity. Bell 103 full-duplex protocol is implemented and the plotter can provide the terminal with an echo as needed.

Software Support

While the 7221A's binary interface language is designed to make programming easy, many users would prefer to program the plotter in a high-level language, such as FORTRAN. HP-PLOT/21, a software support package for the 7221A, is a set of FORTRAN subroutines that make this possible. Two versions of the software package are tailored specifically for use with HP 3000 Series II and GE Mark III computer systems.

Acknowledgments

The 7221A design was based heavily on the prior design of the 9872A, whose contributors are acknowledged. In addition Bob Haselby wrote large portions of the new firmware and designed the new interface. Al Kendig wrote the character generator, Dale Schaper provided the self-test firmware and modifications to the electronics, and Hank Swart designed the mechanical modifications. Ken Yamamoto and Ed Dufour wrote the HP-PLOT/21 software support package and provided product definition and development assistance. 🄷🄿

Speed, Precision, and Smoothness Characterize Four-Color Plotter Pen Drive System

by Marvin L. Patterson, Robert D. Haselby, and Richard M. Kemplin

PERHAPS THE MOST OBVIOUS and most frequently criticized aspect of an X-Y plotter is the quality of the lines that it draws on paper. This depends not only on the quality of the ink line made by the pen, but on the smoothness of the control system and the precision of line endpoints as well. Precision is necessary so that lines drawn to the same point from various places on the plotting surface will close. Smoothness is required for proper operation of the pen and to keep the velocity vector at the pen tip exactly in the desired direction throughout the move. If the control system fails in either of these require-

ments, the pen indelibly records the mistakes for all eyes to see.

Comparison of Control Systems

Traditionally, dc servo control systems have provided the highest-quality pen motion control with their inherent smoothness of operation. They have limitations, however, in that low deadband and matched X and Y-axis dynamics are difficult to achieve while maintaining adequate loop stability. Unless the dynamic response of the X and Y axes are closely matched, pen motion during acceleration and deceleration will deviate from the desired line. Excessive deadband causes the start of motion in the slow axis to lag behind that of the fast axis when a line is being drawn with a very high or very low slope. Endpoint precision is also reduced by deadband. The answer to both of these problems is higher loop gain, but this reduces the stability margin. Thus servo control systems inevitably reach a trade-off between performance and stability.

Microstep-controlled step motors provide answers to some of these concerns but introduce their own problems. Step motors typically provide an increased position control stiffness that produces a corresponding decrease in deadband. Since the control system is usually open-loop, no stability trade-offs exist. A step motor, however, behaves like a torsional spring about its equilibrium point. This, coupled with inherently high rotor inertia, gives rise to a low-frequency electromechanical resonance not found in dc servos.

When microstep control is applied to achieve improved resolution, decreased position accuracy and nonuniform torque characteristics become apparent. During constant-velocity operation, periodic perturbations caused by the nonuniform torque can interact with the electromechanical resonance to produce severe oscillations in the rotor velocity.[1,2] In an X-Y plotter, these oscillations cause the pen to draw wavy lines. Studies have shown that the human eye can easily detect periodic perturbations in a line in the frequency range of one to five cycles per centimeter having amplitudes as small as 0.05 mm peak-to-peak.

The control system used in the HP 9872A and HP 7221A Plotters overcomes these problems through an improved mechanical drive coupled to an advanced microstep control system that features adjustable phase current waveforms. The combination of these improvements provides smoothness and precision never before available in a comparable product.

The Mechanical Drive

Design objectives for the mechanical drive system, in addition to superior line quality, included low cost, quiet operation, easy servicing and access, reliability, and low maintenance.

A flat piece of sheet metal is punched to mount the various components; this has the advantages of simplicity and minimum tooling. Experience with earlier recorders showed that those with the least mechanical play produce the cleanest lines. Play is caused by necessary gear backlash and bearing clearances on tracks, especially the former, so the new design has no gears. Instead, the block-and-tackle principle is used (see Fig. 1). A needed speed reduction of 2:1 was achieved with the minor penalty of using eight pulleys instead of the usual four on the X-axis. This penalty was considered more than cancelled by the absence of play between the drive motor and the pen arm and by the great reduction in audible noise, cost, and maintenance compared to a gear-train drive.

The same speed reduction principle is used in the Y axis but with more complexity because of the need to avoid the plotting area with the Y-axis drive cable. The Y-axis motor is in a fixed position beneath the plotting area. Its drive cable goes up to the pen arm and then returns to a plane below the plotting area. This requires a total of 12 pulleys. Because of severe space limitations in the pen arm, a much smaller pulley is used than those in the X axis. This is possible because a much smaller load is being driven so a very small cable can be used.
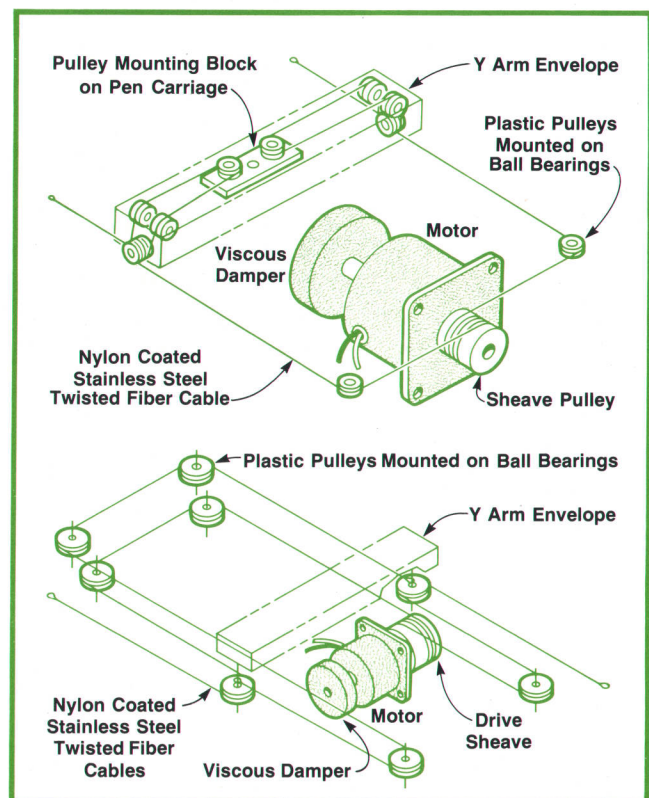

Fig. 1. *Pen drive system has no gears. Advantages are an absence of mechanical play and a reduction in audible noise, cost, and maintenance.*

Labels on figure:
- Cutouts for Pulleys and Cables
- Hardened Steel Rod
- Linear Ball Bushing Pair
- Dust Caps with Oiled Felt Wipers
- Hardened Steel Rod and Extruded Aluminum Track for Y Axis Pen Carriage Motion
- Aluminum Die-Cast Front and Rear Blocks
- Aluminum Rear Track
- Wheel Adjustment Slots
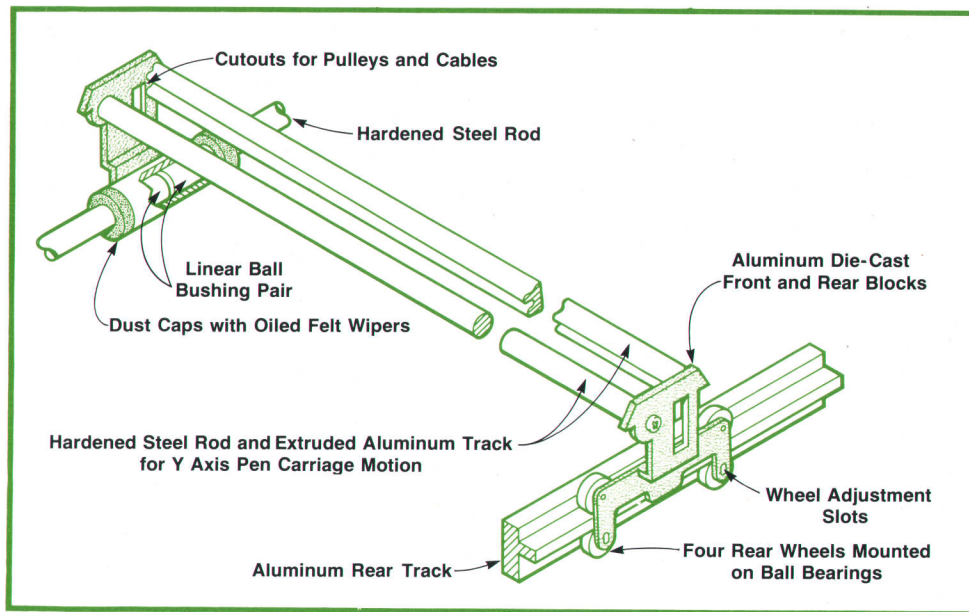- Four Rear Wheels Mounted on Ball Bearings

Fig. 2. *Linear bearings help reduce play and extend drive system life. They guide the pen arm in all directions except rotationally. Rotation is controlled by plastic wheels on an aluminum track.*

Linear Bearings

Long drive system life and minimum play are achieved by the use of linear ball bearings as the prime guiding element of both the X and Y axes. To attain greater axial stability, two linear bearings are used in tandem. They are pressed into a die-cast housing that ties the pen arm, linear bearings, and drive cable together. Because of greater weight and span requirements, the X axis uses a 12.8-mm-diameter, stainless steel, hardened shaft while the Y axis uses a smaller 9.5-mm-diameter shaft.

To protect the bearings from contamination, felt wipers are installed at each end of the housing and held in place by snap-on nylon caps. These wipers are impregnated with a light oil to provide lubrication for the bearings while at the same time keeping the shaft clean. In life tests these bearings have run as many as 450 miles with no sign of failure. During these tests it was not necessary to replenish the oil in the wipers.

The linear bearings guide the arm in all directions except rotationally. To control this, the opposite end of the pen arm is retained by plastic wheels on an anodized aluminum track (Fig 2). The lower wheels are adjusted to minimize the clearance.

Resonances and Damping

The drive system is essentially a two-spring, two-mass system. The torque-producing mechanisms in the permanent magnet step motor are, in effect, a magnetic torsional spring with an approximately sinusoidal spring constant. When the position of the motor shaft is nearly in phase with the currents applied to the motor winding, the motor can be approximately modeled as a linear torsional spring coupled to the rotor inertia. This creates a resonant system with a natural frequency of about 180 Hz.

Coupled to this through the sheave pulley, the cable-and-pulley arrangement attached to the pen carriage and drive mechanics adds a second spring mass system with a natural frequency of about 230 Hz. The two resonances are tightly coupled and lightly damped, so the mechanical system can cause amplified response to perturbing influences at certain frequencies.

A mechanical damper is attached to the free end of the motor shaft to reduce this tendency. This damper consists of an inertial mass that is free to rotate in a bath of controlled-viscosity silicon oil. The outer housing is sealed with O rings and clamped to the motor shaft. With both the damper and mechanical load connected, the first resonant frequency of the X axis is reduced to about 60 Hz. The damping action provided by the dampers reduces the amplitude of the response of both axes from about 16 dB to approximately 8 dB at the worst-case frequency.

The Microstep Control System

In spite of the reduction of the resonant response provided by the dampers, harmonic torque perturbations can interact with the remaining resonant peak to create oscillations in the rotor velocity during long moves (see Appendix, page 19). This causes the pen to draw wavy lines at certain critical slopes and velocities. Properly adjusting the waveform of the motor phase currents reduces these perturbations to a negligible level, and provides control smoothness previously available only from dc servo control systems (see Appendix). The objective of the control electronics is to provide position control of the pen through the application of such waveforms to the step motors.

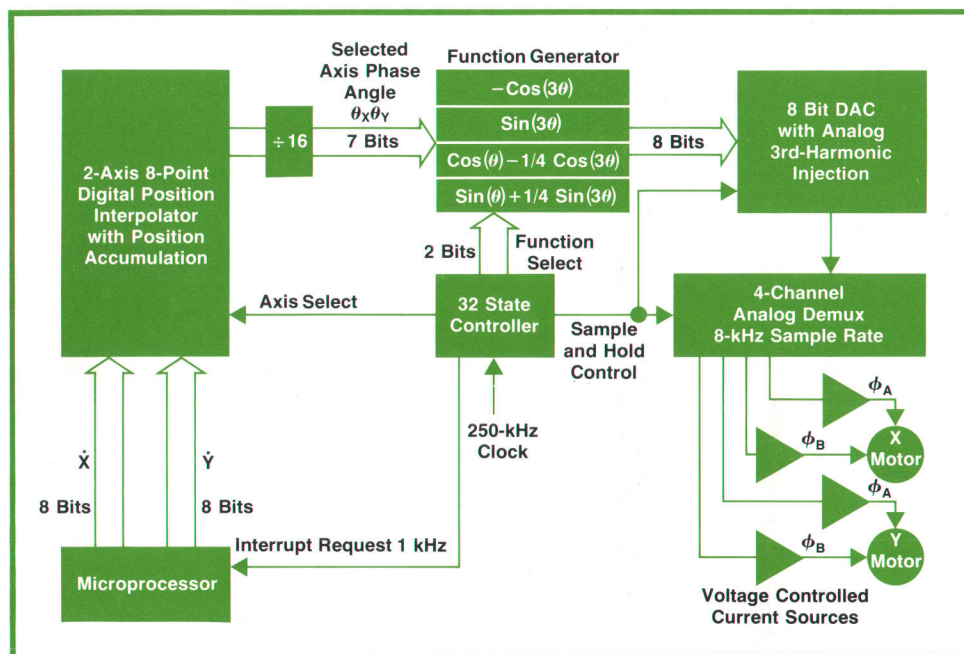A block diagram of the microstep control system is

Fig. 3. *Microstep control system uses step motors to move the pen to the required position. Open-loop system avoids the performance-vs-stability problems of dc servo control systems.*

shown in Fig. 3. The control system consists of an interpolator circuit for each axis, a time-multiplexed waveform generator, and two phase current drive amplifiers for each axis. The interpolator circuit converts a digital velocity word produced each millisecond by a vector generation algorithm in the microprocessor into a position control signal that drives the waveform generator. The waveform generator converts X and Y position signals into A and B phase voltage waveforms for the X and Y motors. These voltages are converted into currents by conventional class A current-drive amplifiers.

Interpolator

The velocity word provided to the interpolator by the microprocessor each millisecond is an eight-bit signed two's complement word. The interpolator output is a series of eight discrete steps occurring at 125-microsecond intervals, one seven-bit word for each of the X and Y axes. This is, in effect, a digital integration process that involves the accumulator and adder shown in Fig. 4. The incoming digital velocity is added to the contents of the accumulator eight times each millisecond. The digital value in the accumulator increases or decreases in eight identical increments equal in size to the applied velocity word. To scale the velocity properly, the output of the accumulator is divided by 16 by ignoring the four least significant bits. The accumulator output provides the required position signal for the waveform generator.

Operation of the interpolator is modulo 2π, so that an overflow returns the position control signal from 2π back to zero. The waveform generator is also modulo 2π, so an overflow causes no discontinuity in the output signals.

The phase current waveforms contain fundamental and third harmonic components. The Nyquist sampling theorem requires at least six samples in each cycle of the waveform to avoid loss of information. This requirement is inherently satisfied by the interpolator implementation. In the worst case, a full-scale positive or negative velocity word causes the interpolator output to advance in average increments of $\pm 2\pi/16$. Thus there are at least 16 samples in every cycle of the generated waveform.

Waveform Generator

A and B phase waveforms are generated for the X and Y motors by a single time-division multiplexed waveform generator circuit (Fig. 5). This circuit provides a sinusoidal waveform plus an adjustable third-harmonic component to each of the four current drive amplifiers. Both the sense and the amplitude of
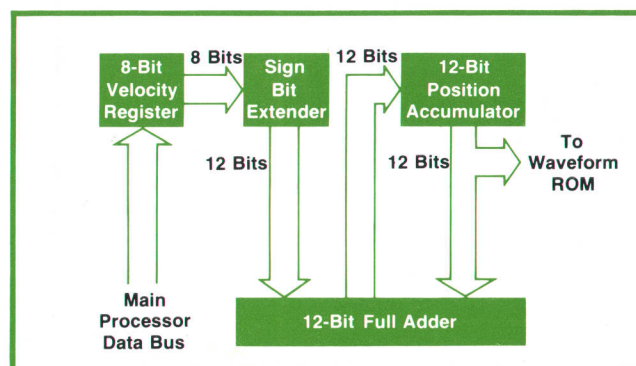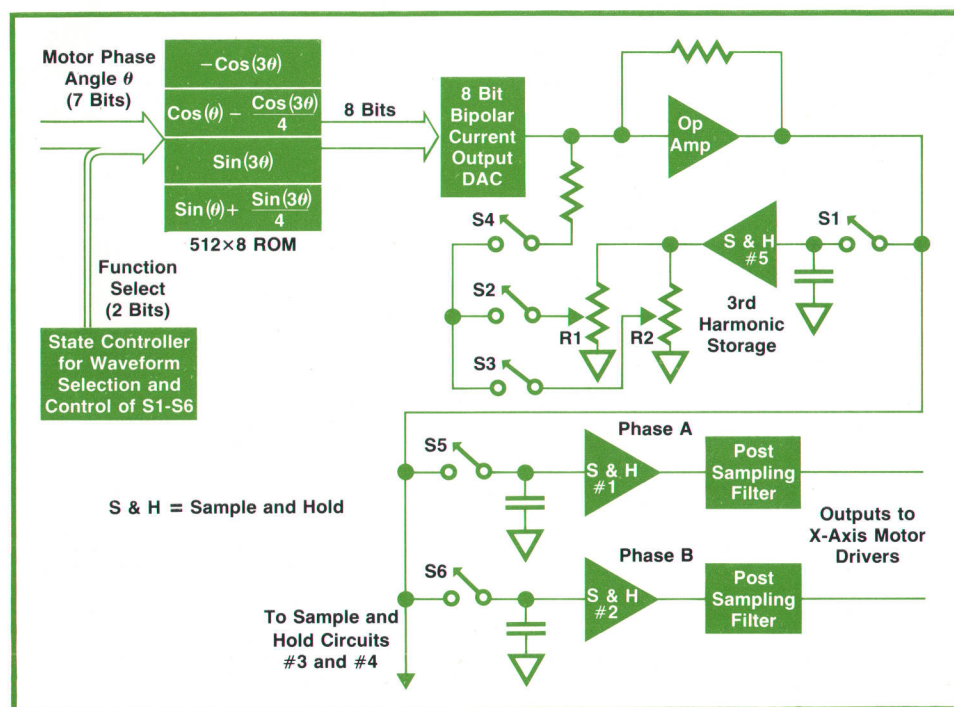

Fig. 4. *Interpolator receives a velocity word from the microprocessor every millisecond. Its output is a series of eight discrete X and Y position steps.*

16

Fig. 5. *Waveform generator produces A and B phase waveforms for the X and Y motors. An adjustable third-harmonic component is added to provide smoothness and precision not previously attainable with step motors.*

the third harmonic can be set independently for each axis.

X and Y position data words from the interpolator are time-multiplexed together to form the least significant bits of the nine-bit ROM address. The two most significant address bits are set by a state control ROM to define which of the four parcels in the waveform ROM is addressed. The four ROM parcels are the A phase third harmonic, the A phase fundamental plus third harmonic, the B phase third harmonic, and the B phase fundamental plus third harmonic. Each of these parcels consists of 128 eight-bit words.

At the beginning of a period, the X position is present in the ROM address, analog switch S2 is closed, and S3 is open. The two high address bits are set so that the A phase third harmonic is addressed. After the digital-to-analog converter (DAC) has had time to settle, S1 is closed long enough to load the third harmonic sample into sample-and-hold circuit number 5.

Next, the high address bits are changed to access the parcel containing the A phase fundamental plus third harmonic. At this time S1 is open and S4 is closed. Once the DAC has settled, the output of the summing amplifier consists of the A phase fundamental and an adjusted amount of third harmonic. The adjustable third harmonic level added to the waveform through S2 is out of phase with that preloaded into ROM parcel 2 so that the resultant level is adjustable from negative through zero to positive. After the A phase waveform has settled, S5 is closed to set sample-and-hold circuit number 1. The output

of this circuit is a stairstep approximation of the desired continuous current waveform. Post-sample filtering smooths this signal into its final form.

The B phase waveform is generated similarly by first addressing the B phase third harmonic parcel and loading sample-and-hold circuit number 5. The B phase fundamental plus third harmonic is then added to the adjusted third harmonic component to produce the B phase waveform. S6 is closed momentarily to set sample-and-hold circuit number 2. The action to this point is completed in the first half of the 125-microsecond period.

During the second half of the period, S2 is open, S3 is closed, and the seven-bit Y position word is connected to the lower part of the ROM address bus. Waveforms are constructed in the same manner as before except with adjustment provided by R2. Stairstep approximations of the Y-axis phase current waveforms appear at the outputs of sample-and-hold circuits number 3 and 4.

Control of the two data control bits, the multiplexer, and the eight analog switches is provided by a state control ROM not shown in Fig. 5. This ROM is addressed by a state counter driven by the system clock. The bit pattern programmed into this ROM establishes the sequence of operation described above.

Controller Adjustment

Four adjustments are provided for each axis of the control system to allow its performance to be optimized for the actual operating environment.[3] First, dc offset can be adjusted in both phase current drive

17

amplifiers. Next, each B phase current amplifier provides a vernier gain adjustment that allows equalization of the magnetomotive force developed by the A and B phase currents. Finally, a single adjustment for each axis sets the level of third harmonic in the phase current wave form. This minimizes the level of fourth harmonic torque developed by each motor. An internal self-test feature aids in the adjustment of these controls.

Plotter Performance

The mechanical linkage in each axis connecting the motor shaft to the pen tip causes 0.25 mm (0.01 inch) of motion for each motor step. Each cycle of the waveform generator advances the rotor by the angular pitch of one rotor tooth, the equivalent of four steps. Thus the pen moves one millimetre for each cycle out of the waveform generator. There are 128 increments in the address to the ROM in the waveform generator, so each increment is equivalent to 0.008 mm (0.0003 inches). The maximum magnitude of the velocity word produced by the vector generator algorithm is 90 binary units, which causes the ROM address to advance by 45 counts each millisecond. This produces a maximum axial velocity at the pen of about 360 mm/s.

The vector generator algorithm in the microprocessor accepts movement commands to a resolution of 0.001 inch or 0.025 mm, which is approximately three times greater than the minimum control system increment. The algorithm converts these move commands into X and Y velocity profiles that accomplish the required move. The maximum velocity attained in a long move by either axis can be varied under user program control in 10-mm/s increments from a minimum of 10 mm/s to the maximum value of 360 mm/s. This allows the user to optimize the pen speed and associated writing quality for any given drawing media. The maximum axial acceleration established in the velocity profiles is about 4000 mm/s² (160 in/s²) or 0.4 g. When the user has programmed a lower than maximum velocity, however, the algorithm assumes that line quality is more important than speed. The acceleration is then halved to further eliminate any minute acceleration transients from the drawn vectors.

Acknowledgments

The mechanical characterization with the resultant inertial matching and mechanical damping was developed by Majid Azmoon and George Lynch. George Lynch also designed much of the Y axis arm. Steve White developed the voltage controlled current source motor drivers. *hp*

References

1. P.J. Lawrenson and I.E. Kingham, "Low Frequency Resonances", Proceedings of the International Conference on Stepping Motors and Systems, University of Leeds, England, 15-18 July 1974.
2. G. Sigh, A.C. Leenhouts, and E.F. Mosel, "Electromagnet Resonance in Permanent Magnet Step Motors", Fifth Annual Symposium on Incremental Motion Control Systems and Devices, B.C. Kuo, Editor; University of Illinois, 1976.
3. M.L. Patterson, "Analysis and Correction of Torque Harmonics in Permanent Magnet Step Motors", Sixth Annual Symposium on Incremental Motion Control Systems and Devices; B.C. Kuo, Editor; University of Illinois, 1977.
4. M.L. Patterson and R.D. Haselby, "A Microstepped X-Y Controller with Adjustable Phase Current Waveforms"; Sixth Annual Symposium on Incremental Motion Control Systems and Devices; B.C. Kuo, Editor; University of Illinois, 1977.

Robert D. Haselby
Bob Haselby developed the 9872A/7221A's motor drive signal generation circuitry and the 7221A's RS232C interface hardware and firmware. He's the co-author (with Marv Patterson) of a paper on microstep control. Bob grew up on a farm in Indiana. After six years in the U.S. Navy Submarine Service, he returned to his home state to attend Purdue University, receiving his BSEE degree in 1972 and his MSEE degree in 1973. He still goes to sea, but now it's for fun, on a sailboat. Bob and his wife and son live in Escondido, California.

Richard M. Kemplin
Dick Kemplin has been a draftsman and product designer with HP for 23 years. He helped develop the pen changer, mechanical drive, and deck design of the 9872A/7221A Plotters. He's listed as inventor in five patents on X-Y recorder mechanical design. Dick was born in Glendale, California. He received an AA degree from John Muir College in 1952, then spent two years in the U.S. Army Corps of Engineers before joining HP in 1954. He's married, has four children ranging in age from 9 to 21, lives in Poway, California, and is half owner of a Commanche 250 aircraft, which he flies whenever he can.

APPENDIX
Correction of Non-Ideal Step Motor Behavior

The motors used in the 9872A and 7221A Plotters are four-phase permanent magnet step motors with 200 steps per revolution. Phases 1 and 3 are connected in series, as are phases 2 and 4, so the motor appears externally as a two-phase inductor-type synchronous motor. Torque is developed independently by each phase in the configuration and is given by [3]

$$T_A = \frac{E_{gA}I_A}{\dot{\theta}}$$

$$T_B = \frac{E_{gB}I_B}{\dot{\theta}}$$

where $\dot{\theta}$ is the angular velocity of the rotor, E_{gA} and E_{gB} are the voltages induced by the permanent magnet in the two phase windings, and I_A and I_B are the applied phase currents. When the rotor velocity is constant the torque produced by each phase is simply the product of two time-periodic waves. The waveforms of E_{gA} and E_{gB} vary with the particular motor and depend primarily on the air-gap geometry between the stator poles and the rotor. The applied phase current waveforms are specifiable and can be adjusted to improve the smoothness of the motor operation.
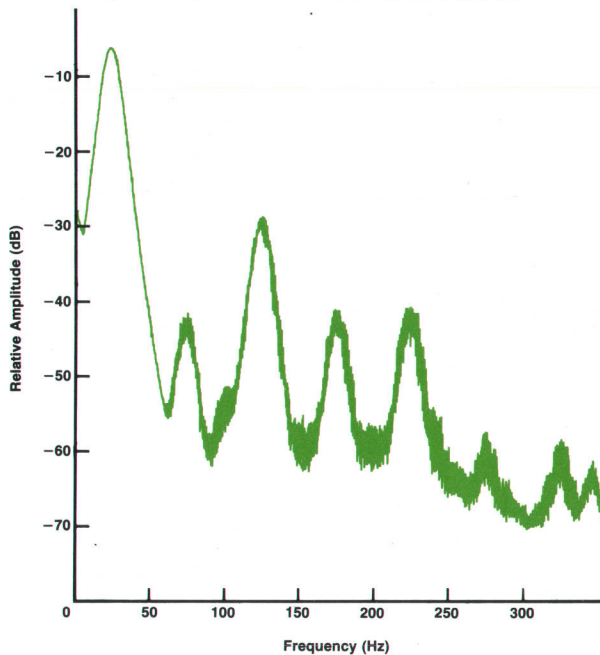

Uncorrected   **Corrected**

Fig. 3. *Fourth-harmonic torque results from phase current fundamental interacting with third and fifth motor harmonics. To reduce this effect, third harmonic is added to the phase currents.*

Fig. 1. *Spectrum of typical step motor generated voltage waveform.*

ages induced at each stator pole to reinforce at the external phase terminals. On the other hand, the even harmonics will, ideally, cancel. This creates the peculiar odd harmonic nature seen in the spectrum shown.

At constant rotor velocity the spectrum of the torque produced by the A phase stator poles can be found by convolving the spectrum of E_{gA} with that of I_A. This convolution is shown graphically in Fig. 2 for I_A equal to a cosine wave at the fundamental frequency of E_{gA}. The resulting torque spectrum is as shown, with a major component at dc and other non-ideal terms at the even harmonic frequencies.

The total shaft torque of the motor is the sum of the A and B phase contributions. In a properly driven, symmetric motor the B phase torque waveform is identical to that of the A phase except for a one-fourth-period delay. When the two torque waveforms add at the rotor, this delay causes the torque harmonics at 2, 6, 10, . . . times the phase current frequency to cancel exactly. The torques produced at dc and the 4th, 8th, . . . harmonics reinforce exactly. Since only dc torque is desired to keep the rotor moving smoothly at constant velocity, the higher harmonic terms represent non-ideal effects in the motor that tend to perturb the rotor velocity. When the frequency of these harmonics falls on a mechanical resonance, exaggerated oscillations can occur in the rotor motion.

The dominant non-ideal torque component is typically the fourth-harmonic terms. Reference 3 shows that the magnitude of this component can be significantly reduced by adding a third-harmonic component to the waveform of the A and B phase currents. Fig. 3 shows how the fourth-harmonic torque is the result of the phase current fundamental interacting with both the third and fifth harmonics in the motor spectrum. A properly adjusted third harmonic in the current waveform will interact with the fundamental voltage from the motor to produce a corrective fourth-harmonic torque term that significantly reduces the magnitude of the resultant non-ideal torque.
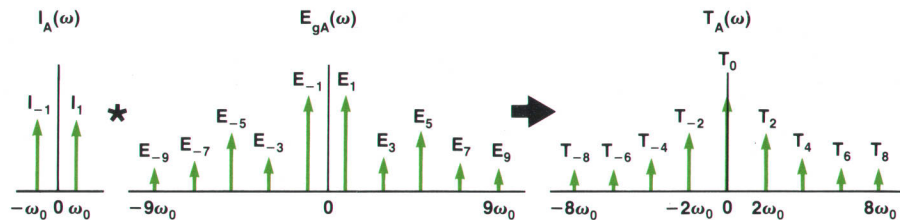

Fig. 2. *Convolution of current and voltage waveforms produces torque spectrum of the A phase stator poles. Major torque component is at dc. There are non-ideal terms at even-harmonic frequencies. Typically the fourth-harmonic terms dominate.*

Insight into the non-ideal behavior of the motor can be gained by examining the nature of the characteristic motor waveform apparent in the open-circuit voltages E_{gA} and E_{gB} when the rotor is turned at constant velocity. An ideal motor under these conditions would produce sinusoidal voltage waveforms. In contrast, the spectrum of a typical generated waveform is shown in Fig. 1. The interconnection of internal stator windings to form an external two-phase configuration causes the odd harmonic volt-
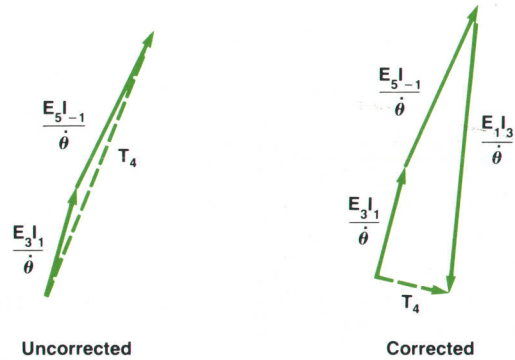
The microstep controller used in both the 9872A and 7221A digital plotters provides an adjustable third-harmonic component in the phase current waveforms. This allows the smoothness of plotter operation to be optimized for each individual motor, thus providing uniform line quality from one machine to the next.

-Marvin Patterson

Pen and Ink System Helps Assure Four-Color Plotter Line Quality

by Leonard P. Balazer, George W. Lynch, Richard M. Kemplin, and Larry W. Hennessee

PENS FOR THE NEW FOUR-COLOR PLOTTERS have been carefully designed to contribute to the plotters' high-quality, precisely defined, and aesthetically pleasing graphical presentation, a presentation that, directly from the plotter, can enhance engineering reports, proposals, and other critical communication documents. In pursuit of this goal the individual properties of a high-quality graphical presentation were first dissected, defined, and cataloged. Desirable qualities, such as appropriate line width, line width uniformity, color density, line registration, and absence of feathering or bleeding became the design objectives for the pen and ink system.

Although the automatic pen changing concept introduced formidable new problems of dimensional control concerned with line registration, the first order of priority was to attack problems that have always haunted the disposable pen. Of these, line width control and line width uniformity are the most difficult. The writing tip tends to flatten and produce an excessively wide line under the influence of the impact forces generated when the pen is dropped onto the platen. These forces, together with the flattening effects of abrasive wear as the pen scrubs across the paper, can cause line width to grow from an initial 0.13 mm to 1 mm or more after writing several meters. Not only does this produce an obvious disparity in line widths as a new pen deteriorates, but also the line can become so wide that it masks information details and closes the loops in small text characters. Another line control problem is seen at high writing speeds, where a pen may fail to produce a dense, easily discernible trace.

Of the several possible ways of drawing a line, such as the capillary pen, the ball point pen, the pencil, and so on, the disposable fiber tip pen was selected as having the greatest potential for meeting all requirements. The ball point pen required too much force against the paper and did not start well. The capillary pen was messy and often lost its prime. Extruded plastic tips did not deliver a sufficient ink flow at high speeds and often developed a wear flash that shut off the ink ducts.

The Nib

Of all the elements of a disposable fiber tip pen, the nib and the ink are the two most important. The first question we addressed was whether to make or buy the nib.

The alternative of making our own nib, a subject we knew nothing about and had no equipment for, was relegated to last place among the various ways of proceeding. Another alternative was to buy and use a modification of an existing instrument or handwriting pen made by another manufacturer. However, no suitable pen could be found. The search was not superficial and involved pens ordered from every manufacturer in the world who somehow managed to make his existance known through advertisements, listings, or references. Some 50 different pens were evaluated and rejected.

It turned out that at least seven manufacturers of fiber nibs exist in the world and each makes several varieties of nibs. All supplied us with samples. The samples were evaluated according to criteria important to us and graded relative to one another. We quickly realized that the most serious general nib problem is uniformity. After extensive investigation into the processes of nib making, we also realized that fiber nib making is more an art than a science, and that the makers of good nibs know very little more why their nibs are good than the makers of poor nibs know why their nibs are bad (careful production control, of course, being an obvious factor). Fortunately, one nib was found to be quite good. The manufacturer of this
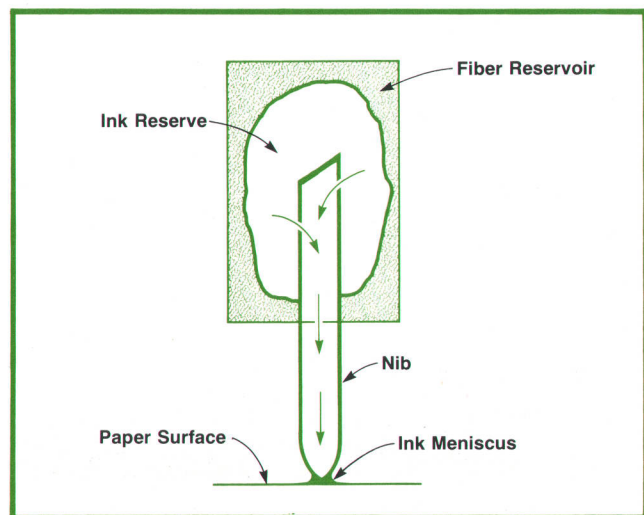

Fig. 1. *Hydraulic system of a pen. The meniscus is the interface between the ink reservoir and the paper.*

nib was unusually cooperative and a series of detailed evaluations of this product was begun.

Since the primary concern was uniformity, four separate nib orders were placed in successive months, and a production sample from ten successive days was obtained. Uniformity was found to be excellent. Thereafter, several iterations in point and shank shape and size were completed and thus the 9872A pen nib was selected. It took two years.

Ink

Fig. 1 shows the hydraulic system of a pen, and the meniscus around the pen tip. As soon as the pen nib touches the paper surface, the annular wedge-shaped interface pulls out ink into this space and the ink sticks and stays in place as the nib moves on, leaving a discernible line.

The nib consists of a loose pack of continuous longitudinal nylon fibers about 0.03 mm in diameter, held together with resin to form an irregular matrix of longitudinal ducts. A cross section of a nib is shown in Fig. 2. As the packing of the fibers becomes more dense, the nib becomes physically stronger, but the interstices through which the ink flows become smaller. Thus as the nib becomes stronger and denser and more able to retain a sharp point while being pounded on the writing platen, the ink flow becomes more restricted. High nib density, of course, also decreases the rate of abrasive wear as the pen is dragged across the paper, and is a desirable characteristic for all considerations except ink flow. Therefore, the design approach was to make the nib as dense as possible compatible with a sufficient ink flow. The way to increase ink flow with a given duct size, in turn, is to decrease its viscosity, so one primary ink requirement
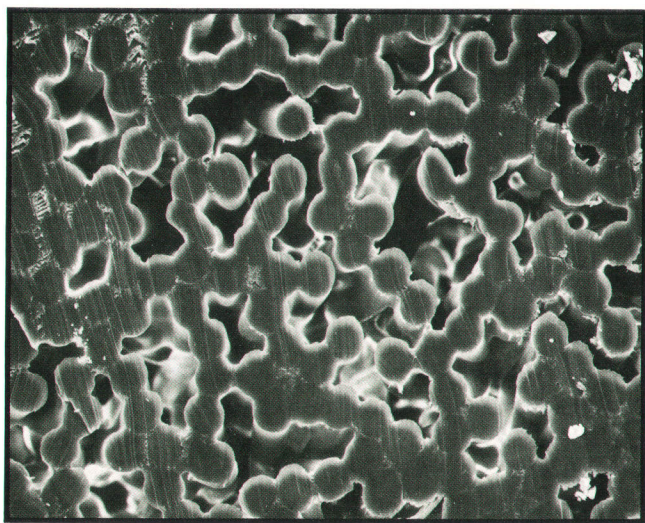

Fig. 2. *Cross-section of a nib, showing fibers and interstices through which ink flows. Nib design requires a trade-off between close packing of the fibers, which aids durability, and good ink flow.*

is low viscosity.

What other characteristics ought a plotting pen ink to have? For one, it must not dry out in the uncovered pen tip too rapidly. The design standard is that the pen should start to write immediately on contact with the paper after having its cap off for up to three days in normal laboratory atmospheres. Hence low volatility is desirable. Fortunately, this property usually comes with high surface tension, which is the source of the force that pulls the ink out of the pen onto the paper.

The ink must wet the paper to form the meniscus and to stay there after the pen has moved on, but it must not wet too well. If it wets too well, the ink-to-paper lateral interface becomes ragged and irregular. This is often called feathering, since tiny feather-like structures sometimes form. When the pen is left stationary against the paper and an ever-growing blob appears around the tip, it is called bleeding.

If the ink does not wet the paper well enough it will tend to form into little balls after the pen moves on. The ideal ink is neutral: it will not spread or retract. The 9872A inks very nearly possess this characteristic on HP graph paper. You can leave the pen on the paper as long as you please, just so it isn't on a fingerprint. This neutrality is responsible for the new plotters' definite and regular ink-to-paper interface that produces the appearance of crispness and cleanness.

Besides having definite paper-wetting characteristics, the ink must enter into a chemical combination with the paper fibers that can be classified as a complicated kind of adsorption. Evaporation is unsuitable as a fixing mechanism since evaporation also takes place in the pen nib and reduces cap-off drying time to unacceptably short periods. Ink that is fixed by evaporation also has the messy tendency to smear under damp finger tips.

Other necessary ink characteristics are color density and stability. Ink dyes are usually organic molecules that deteriorate with time. The period until a definite fading or color change becomes manifest must be at least two years for normal distribution and use. (Printer's black ink does not contain a dye, but lampblack, which lasts forever.) The ink must also be compatible with the nib material as well as the pen structure and not cause swelling, crazing, or stress cracking. Finally, the ink must be retainable, that is, it must not escape through the pen body at an excessive rate.

The 9872A inks were compounded through complicated trade-offs involving all of the above-mentioned factors.

Pen Structure

In the world of fiber tip pens, the 9872A pens have the distinction of being dimensionally precise beyond all others. Lack of dimensional precision is in
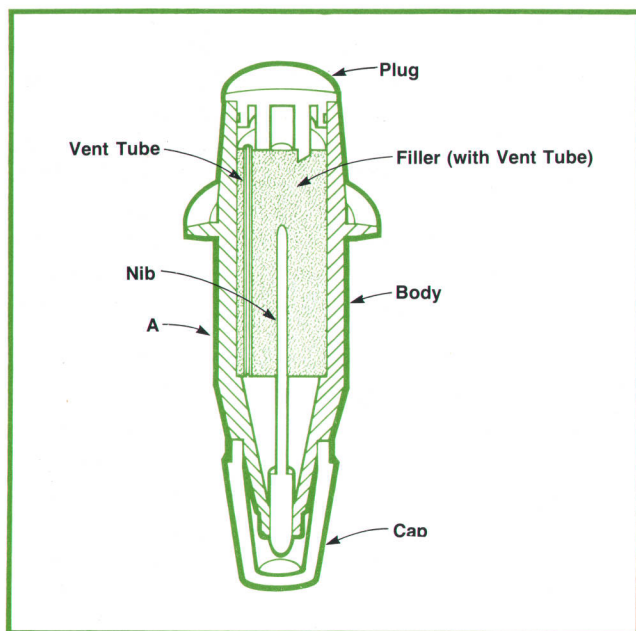
Fig. 3. *Pen structure is designed to prevent leaking at altitudes up to 50,000 feet.*

no way detrimental, for example, to a handwriting instrument. It does not matter one jot if the pen barrel is bowed, or out of round, or eccentric by 0.1 or 0.2 mm. However the 9872A multiple-pen concept and the requirement for exact line registration imposes the need for a hitherto unknown (to HP, at least) level of mechanical precision in the pen.

Fig. 3 depicts the structure of this pen. The bottom of the flange and cylindrical surface "A" are the interface surfaces that control pen position and have to be maintained round, flat, square, and the same size. This requirement eliminated all but the lowest-shrinkage plastic molding compounds. (The alternative of machining these surfaces was rejected on the basis of its high cost.) This also imposes the restriction that these surfaces had to be molded within a single continuous-mold cavity, eliminating alternate designs involving split cavities and side pulls. The four cavities of the four-part mold had to be matched with extreme care beyond the normally high level of moldmaking precision. Also, molding process parameters have to be very carefully controlled to produce well-matched parts.

The pen venting scheme can also be seen in Fig. 3. As an external vent, the round nib fits into a square hole, and the unfilled corners allow air to flow into and out of the interior of the pen. A plastic tube continues the venting from the lower to the upper interior cavity. Without such venting, pressure or temperature changes that cause the air inside the pen to expand would cause ink to be forced out of the pen, producing dreaded leaking. This scheme works well for ordinary handling at ordinary pressures; however,

Digitizing Sight Adds Versatility

The 9872A/7221A Plotter's electronic pen-positioning circuitry incorporates a digitizing capability, that is, it can digitally measure an arbitrary pen position. This is very useful in many data processing and recording applications. Unfortunately, an ink pen is a poor cursor or indicator of pen carriage position, because judging the precise location of the pen is a difficult matter, subject to parallax and confusion by shadows.

A digitizing sight was developed to facilitate the digitizing process by making it easier to position the pen carriage and by vastly improving the accuracy of the process. The digitizing sight is also useful in setting the registration of the pen on pre-lined graph paper or on material previously written and removed and later replaced on the plotter platen.

The digitizing sight is a passive optical device much the same size and shape as the pen (see photograph).

The digitizing sight brings the image of a point of interest together with a superimposed reference point on an elevated plane where it can be viewed from within a 70° cone without parallax effects. The brightness of the image is often enhanced, since image brightness does not depend on the illumination at the platen surface, but on the illumination at the top surface of the sight, which is free of shadows from the pen carriage.

How does the digitizing sight work? Basically the sight consists of a coherent bundle of optical fibers, each of which conducts light gathered at its upper surface down to the writing surface it rests upon. The light reflected from the writing surface is conducted back through the fiber to the upper surface, where it is broadcast to the observer's eye. Each fiber retains its spatial relationships to its neighbors at the upper and lower surfaces so the combined effect of all the fibers is to transmit the image of the material over which the bundle is placed.

Any desired reference marks or reticles can simply be placed on either the upper or lower surface. The digitizing sight has a single spot about 0.5 mm in diameter at its center. A point spot was chosen since the sight interfaces with the pen holder and the stable in the same way as a pen and can be selected or stored in the same manner as a pen. In the transfer process from stable to holder and back, the pen rotates through an arbitrary angle. If crosshairs had been used on the sight they would be delivered at arbitrary angles and so were rejected as reference marks.

In use, the reference point in the digitizing sight must exactly duplicate pen tip position; therefore, although the digitizing sight is a very simple device, the dimensions of the interface surfaces and the location of the reference point are critical and are carefully controlled.

-Leonard Balazer
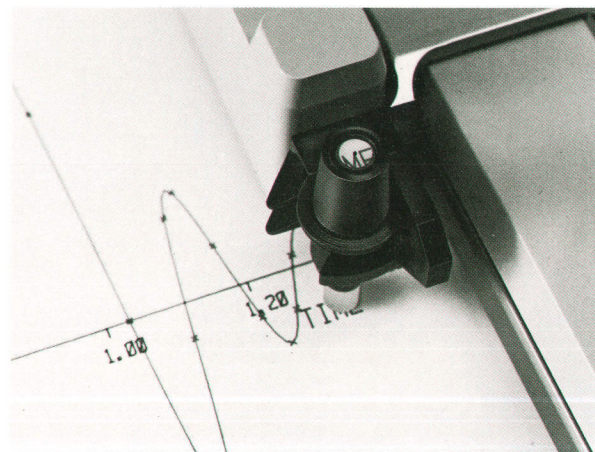
at altitudes above about 45,000 feet, the ink begins to outgas, although it does not boil. This produces a foam that can be pushed out of the pen by further gas expansion. This happens especially in sudden decompressions, such as when the cap or plug is blown off the pen by internal pressure. To prevent this sort of thing, the plug and the cap are equipped with smooth sealing surfaces and assembled to the body with interference fits, so the pen retains normal atmospheric pressure internally for extensive periods at altitudes beyond 50,000 feet without popping off its plug or cap.

When the cap is forced over the nib end of the pen, the pen is tightly sealed, preventing slow evaporative ink loss. This sealing is sufficient for several months at ordinary laboratory environments. However, the water component of the ink escapes through the pen body walls, so for long-term storage, the pens are hermetically sealed in foil pouches that effectively prevent any measurable moisture loss.

Pen Stable and Pen Changer

The pen changing mechanism is perhaps the most interesting mechanical aspect of the 9872A from the user's standpoint. During many demonstrations observers have marveled at the speed with which the instrument changes pens and trace colors.

To minimize its mass, the carriage holds only one pen at a time. An alternative might have been to transport a rotating turret with all the pens on the carriage, but this would have substantially increased the response time of the machine. Instead, all the pens are stored in a four-position "stable", where they are kept capped to prevent them from drying out in arid climates (Fig. 4). When a pen is selected no active elements (e.g., solenoids or motors) are used to effect the change. A ramped surface on the nose of the pen carriage simply drives down a spring-loaded bracket that carries a pen cap away from the tip of the pen. When the pen is removed by the carriage the bracket springs back into its original position. The same spring that returns the bracket also retains the bracket in the stable, so assembly is rapid and simple.

No expensive active elements are used to hold the pens in the stable or carriage. Carefully balanced spring-loaded arms support the pens and the special digitizing sight (see box at left) in both the stable and the carriage. The upper and lower arms that support each pen are identical, as are their return springs and mounting hardware. This helps keep the overall cost of the stable so low that an early plan to offer the stable as a moderately expensive option was dropped.

While the simplicity of the stable precludes the need for much service, the opportunity to provide occasional repair is readily available. A few accessible screws allow the entire control panel to be removed and two screws are removed to expose virtually the entire stable mechanism.

The motions used by the plotter to fetch or store pens are ordinary X and Y moves of the arm. The
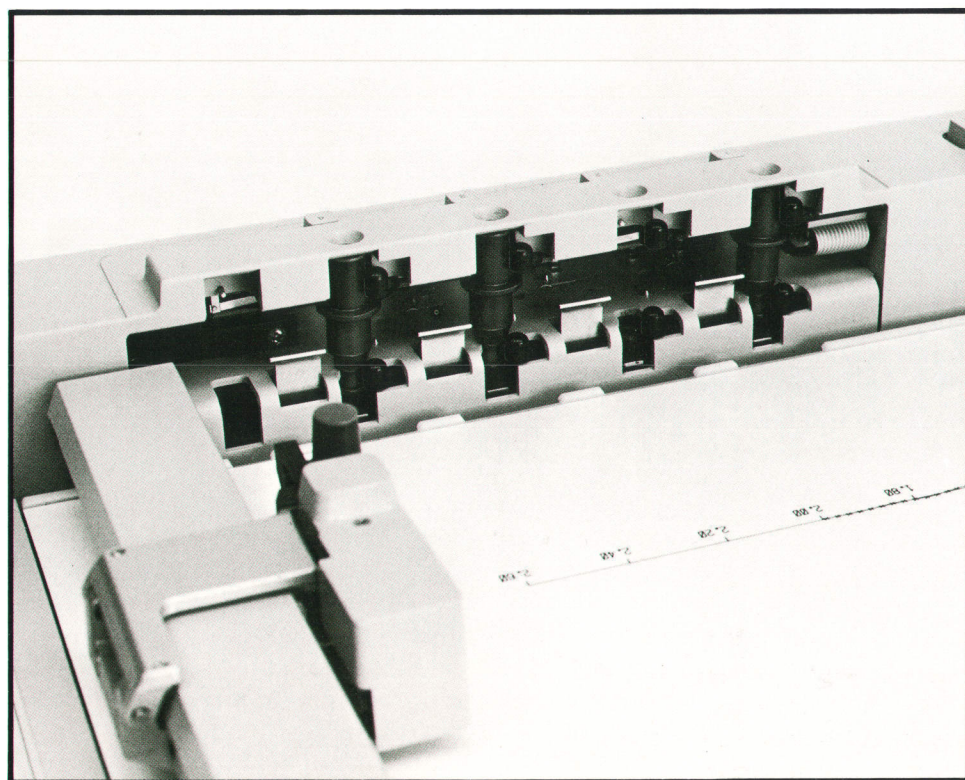

Fig. 4. *Four-position pen stable holds pens of various colors when they are not in use. (Fifth stall is used to determine whether there is a pen in the carriage.) Unused pens are kept capped to prevent ink drying. To change pens, the pen carriage stores the current pen in an empty stall and then picks up the new pen using ordinary X and Y motions.*

patterns for fetching or storing from or to each stable position (stall) are stored in read-only memory (ROM) along with the firmware pen-changing algorithm that moves the arm in these patterns to execute the requested pen change.

Pen change requests are initiated under program control via the input/output system or locally from the plotter's front panel. Requests for a pen from a vacant stall are ignored. Should all four stalls and the arm contain pens, all pen change requests are ignored because the arm must be vacant before it can fetch a pen from the stable.

For the pen-changing algorithm to make such decisions it must be able to detect the occupancy status of each stall and the arm. Each stall is equipped with a microswitch to indicate the presence or absence of a pen. Another microswitch, in a fifth stall not used for pens, detects the occupancy status of the arm. These five microswitches enable the algorithm to avoid fetching a pen from an empty stall or storing a pen into an occupied stall.

Should the plotter be requested to fetch a pen from an occupied stall and there are one or more vacant stalls, the algorithm assumes the arm has a pen, and moves the arm in the pattern necessary to store the pen into an empty stall. If there is more than one vacant stall, the algorithm returns the pen to the stall from which it was originally fetched, unless that stall is no longer vacant (perhaps someone has hand-loaded it), in which case the lowest-numbered vacant stall is selected to receive the pen. After executing the pattern to store the arm's current pen, if any, into a vacant stall the algorithm executes the pattern to fetch the requested pen.
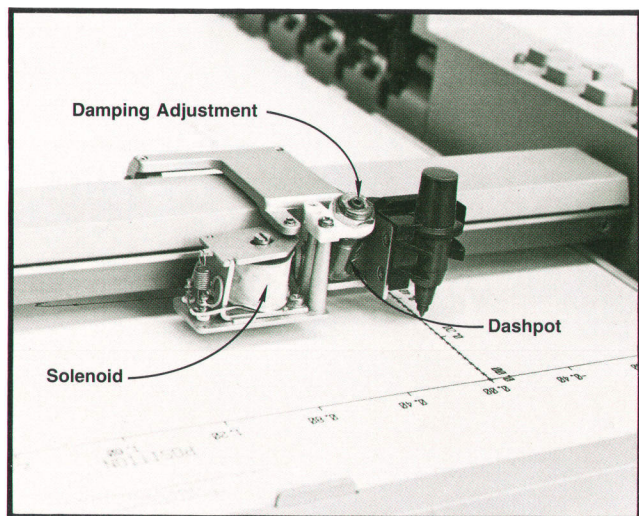
If the plotter is requested to fetch a pen when all
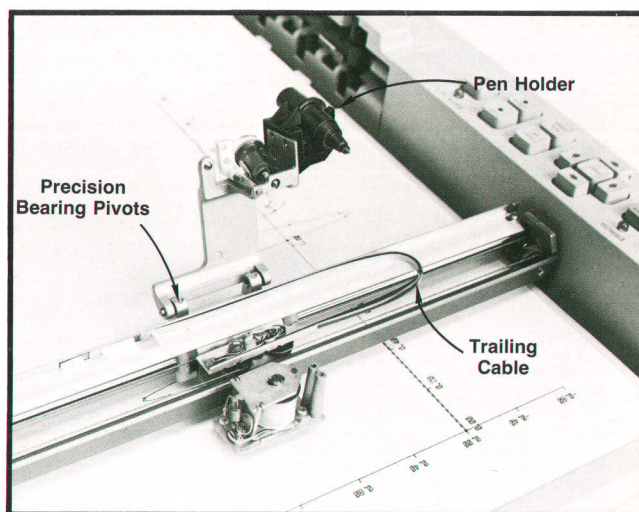
Fig. 6. *Trailing cable provides power to the pen lift assembly.*

four stalls are occupied, the fifth "pen-in-arm" microswitch is used. The arm must be vacant before it can receive a pen from the stable. The algorithm moves the arm to the fifth microswitch, and if the arm is vacant, the pattern to fetch the requested pen is executed. If the arm contains a pen, the pen change request is ignored because there is no vacant stall to receive the current pen before fetching the requested one.

The move pattern to store a pen into a stable is the reverse of the pattern to fetch a pen from that stable. After a pen change, the algorithm returns the arm to its platen position before the pen change request.

Pen Lift Mechanism

Design objectives for the pen lift mechanism for the new four-color plotters included reliable operation and lifetime at least an order of magnitude longer than earlier designs. The life target was set initially at 40 million cycles of operation without any maintenance or service.

When the mechanism lowers the pen it must not slam the pen into the hard platen and smash the pen tip. Once the pen is down and slewing across the paper, the mechanism must hold the pen rigidly or it will chatter and skip, leaving a dotted line.

Before the plotter can begin to draw a line segment, it must pause long enough to lower the pen. The speed with which the plotter can draw such figures as characters or dashed lines depends heavily upon the length of this delay. The new mechanism had to minimize this pen-down delay.

In addition to these objectives, several requirements were imposed by new features designed into the 9872A. With the introduction of the pen stable, the pen holder had to be able to reach off the drawing surface to drop off or pick up a new pen quickly and

Fig. 5. *Pen lift mechanism of the four-color plotter. Pneumatic dashpot controls impact velocity so the pen tip is not deformed, there is no ink blob when the pen is dropped, and the pen does not bounce.*

with 100% reliability. Since the prime movers of the plotter are open-loop stepper motors and have no position feedback, it is possible to overpower the mechanism and displace the arm and pen carriage in such a way that the pen holder crashes into the front panel at full slew speed and with full motor power when reaching for a new pen. The pen lifting mechanism had to be designed to withstand this kind of crash. In the worst-case collision the impact is to the slender lever that clutches the pen.

The pen lift mechanism of the 9872A and 7221A Plotters is shown in Fig. 5. Underneath the pen lift cover is a pneumatic dashpot that helps achieve several of the objectives. The damping rate of the dashpot can be adjusted in the plotter so the pen impacts the table at a rate of about two inches per second. At this velocity the impact with the table top can be easily absorbed by elastic deformation of the pen tip. This prevents mushrooming of the pen tip after successive pen drops so effectively that now the only reason for a pen to become unserviceable is that it runs out of ink. At low impact velocity there is no ink blob where the pen is dropped and the tendency for the pen to bounce upon impact is reduced, permitting a shorter pen-down delay and a faster character plotting speed.

The two major structural pieces of the pen lift assembly are aluminum die castings. They provide compactness, the rigidity to keep the pen from chattering while drawing high-speed vectors, and the strength to withstand impacts into the front panel and pen stable.

Several different high-strength materials were tested for the lever that grips the pen. Most broke upon impact with the corner of the front panel when reaching for a new pen after the arm had been forced out of position. It turned out that a common acetal resin produced an injection-molded lever that was durable enough to withstand repeated worst-case impacts and had the creep resistance to stand up to the stresses produced by the pen gripping spring.

Precision bearings are used in the hinge of the lifting mechanism for smooth operation over a long service life. Life tests were discontinued after 40 million lift-drop cycles with little noticeable wear to critical parts.

Putting the pen-lift solenoid close to the pen reduced the audible noise to a tolerable level and improved overall reliability by minimizing wear and the number of moving parts. It did, however, necessitate development of a trailing cable inside the slender arm. A thin, twin-lead flexible circuit met the flex-life requirements, but pushing that circuit in the return direction into the slender arm was like trying to push a chain by one end; the tangles that resulted were disastrous. Supporting the flexible circuit on each side with a crowned, stainless steel strip provided the

stiffness necessary to control it. The effect is similar to bending a steel tape measure: the straight portion is stiff while bending stresses are kept low in the looped portion. Fig. 6 shows the trailing cable assembly inside the arm.

The pen lift assembly is easy to assemble and service. The three adjustments (pen height, pen force, and damping rate) are accessible from the top after removing one screw and the pen lift cover (Fig. 5). The interior of the arm, shown in Fig. 6, can be exposed by removing one more screw and snapping off the arm cover.

Acknowledgments

George W. Lynch
George Lynch received his BSME degree in 1971 from Oklahoma State University and his MS degree in aerospace engineering in 1973 from California Institute of Technology. He joined HP in 1972, and developed the pen lift mechanism and mechanical drive system of the 9872A and 7221A Plotters. Born in Borger, Texas, he's married and lives in Escondido, California. Before a recent vacation in Hawaii, George occupied his spare time with golf, skiing, and radio-controlled gliders and cars. Now he has a new passion—surfing.

Leonard P. Balazer
Leonard Balazer received his BS degree in physics from Michigan State University in 1954 and his MS in automotive engineering from Chrysler Institute in 1957. With HP since 1972, he's been involved with graphic recorder mechanism and pen design. Born in Chicago, Leonard spent two years in the U.S. Army before enrolling at Michigan State. Before coming to HP, he served for several years as a program manager in the aerospace industry, authoring two successful patent applications on airborne ranging. Now living in San Diego, California, he devotes much of his time to sculpture and the study of language. He has three college-age children.

A Battery-Powered ECG Monitor for Emergency and Operating Room Environments

Electrical isolation, reduced susceptibility to RF and electrosurgery interference, and battery power equip this non-fade ECG monitor to operate in the electrically hostile environments found in emergency vehicles and operating rooms.

by Sherry R. Grobstein and Ronald D. Gatzke

CONTINUOUS MONITORING of a patient's ECG provides one of the important indicators of a patient's physiological status when in surgery or when being transported in an emergency vehicle. It follows, then, that ECG monitoring instruments must be depended on to operate continuously under these circumstances.

This does not always happen. Emergency environments are far more hostile to a monitoring instrument than the usual hospital ward and therefore impose special requirements. For example, the transmitters used by emergency vehicles generate RF interference that is much stronger than any encountered in the hospital. Hence, a monitor for emergency vehicle use must be highly immune to RF interference, as well as being more rugged than those designed for fixed-installation service.

In the operating room, very strong interference is generated by electrosurgical machines, causing the usual ECG monitor to be useless during certain procedures. The operating room also imposes severe requirements on electrical safety. With the amount of electrical equipment involved—fluid pumps, motorized operating table, electrosurgical equipment—

Fig. 1. *Model 78333A ECG Monitor displays ECG waveform and heart rate with minimum interference from electrosurgery equipment or other sources of electromagnetic radiation. Internal rechargable batteries can power the instrument for up to six hours.*

the chances of accidents from improperly grounded equipment are increased. At the same time, the patient's primary protection against electrical shock, the skin, is breached.

Dependable Monitors

The growing need for ECG monitors that can operate safely and reliably in these more difficult environments has led to the development of a new ECG monitor, Hewlett-Packard Model 78333A (Fig. 1). This instrument is rugged enough for mobile use and it is battery-powered for portability. It also incorporates other features that minimize some of the electrical hazards peculiar to battery-powered instruments (see box at right), and it is highly resistant to RF interference.

The new monitor presents a single ECG waveform on a non-fading CRT display along with a horizontal bar graph that indicates heart rate. In addition to the visual display, it gives an aural indication by means of a "beeper" that makes attending medical personnel aware of cardiac events without requiring them to watch the CRT. It beeps in response to each R wave and variations in the pitch provide an indication of arrhythmias, giving immediate warning of trouble. A steady tone in the beeper indicates an INOP (inoperative) condition. Adjustable heart-rate alarm limits are indicated visually on the bar graph and audibly by the beeper, which generates a steady tone when limits are exceeded. A lead selector switch gives a choice of the twelve electrode lead connections commonly used by cardiologists.

The instrument is powered either by ac line power or by internal gel-type lead-acid batteries that can operate the instrument for six hours when fully charged. The batteries recharge whenever the instrument is connected to an ac line, and the changeover from battery to ac line operation occurs automatically when the ac line cord is connected.

To prevent damage to the batteries from complete discharge, a front-panel lamp starts to flash when an operating time of about 30 minutes remains on the batteries. At the conclusion of the 30-minute warning interval, the instrument automatically shuts itself off to prevent deep discharge of the batteries.

The efficiency of the switching regulated power supply in these instruments permits them to operate over a wide range of line voltages (+10%, −25% of nominal) without danger of excessive power dissipation. They are thus essentially "brown-out-proof."

Instrument Organization

A simplified block diagram of the Model 78333A ECG Monitor is shown in Fig. 2. The ECG signal is sensed differentially by the RA and LA (right arm, left arm) electrodes and, as indicated by the diagram, it is

filtered, amplified and used to modulate a 102-kHz carrier. The modulated carrier is transformer-coupled out of the floating and guarded input enclosure, demodulated, amplified further, and applied to an analog-to-digital converter. The converter samples the waveform at a rate of 250 samples/second, converts each sample to an 8-bit parallel word, and enters the word into the recirculating memory where it replaces the oldest word stored.

Safety Problems in Battery-Powered Instruments

Battery-powered medical equipment has a unique problem: lack of a connection to ground. Whereas this is most often considered a safety advantage, it can be a hazard if the patient or operator becomes the link from the equipment to ground for a dangerously high current.

Modern ECG monitors prevent the completion of a current path from some other source through the patient to ground by isolating the patient electrodes from the instrument's ground. The ECG signal is transferred from the floating guarded input circuit to the main chassis circuits by optical or transformer coupling.

In the usual instrument, the floating and chassis grounds are connected by an 800-volt spark gap that provides a controlled breakdown to protect the amplifier in the event that a high voltage is coupled to the ECG electrodes. When the spark gap fires, the gap voltage drops close to zero so any exposed parts on the floating circuits will not reach hazardous potentials. Battery-powered instruments do not have this kind of protection.

If an operator happened to be touching an exposed metal part on an ungrounded battery-powered instrument that was monitoring a patient undergoing defibrillation, the operator could be exposed to a high voltage (a defibrillator applies a short, high-voltage pulse—5 ms wide, 8-16 kV high—to wide-area electrodes on a patient's chest to restart or resynchronize heart muscles that are fibrillating, that is, working in an uncoordinated and hence ineffective manner).

Another operator safety problem arises during electrosurgery. Electrosurgery machines apply several hundred volts of RF between 0.4 and 5 MHz to the patient to cut tissue or coagulate blood vessels. At 1 MHz, the typical 50-pF stray capacitance between the floating input circuits of a monitoring instrument and the main chassis is only 3 kΩ, so an operator touching any exposed part connected to the main chassis of an ungrounded instrument during electrosurgery could complete a low-impedance path to ground, and suffer a shock or a burn as a result.

These hazards are eliminated in the new 78333A Monitor by the 25-kV electrical isolation provided in the cabinet design. All patient-connected circuits, cables, and connectors are isolated from any chassis-grounded component by one-inch air gaps or 1/16 inch plastic insulation. Signals are coupled out and power is coupled into the floating circuits by transformers that can withstand 25 kV between primary and secondary.

In addition, control knobs are mounted on plastic shafts that connect to the controlled component. Instrument covers and front and back panels are plastic and there is at least ½ inch of air between chassis metal and anything on the outside of the instrument that the operator can touch. Exposed screws and metal in the handle are also isolated from the chassis.

Electrosurgery Interference

Electrosurgery is being used more and more widely because it makes nearly bloodless incisions, greatly shortening certain surgical procedures. However, it also creates a high level of RF interference, very often obliterating the ECG waveform displayed on a monitor.

Electrosurgery machines generate RF signals within a range of 0.4 to 5 MHz with peak-to-peak amplitudes of 100 to 1000 volts, pulse-modulated at rates from 1.5 to 25 kHz for coagulating, or 120 Hz for cutting. The RF is applied through a pointed scalpel at the point of incision and the current return is through a wide-area electrode on the opposite side of the patient's body.

The ECG signal, on the other hand, is on the order of 1 mV with frequency components below 100 Hz. There are many places—on the patient, in the electrosurgery machine, in the ECG monitor—where the electrosurgery RF is demodulated, producing interference in the ECG display. The scalpel-tissue interface, the ECG electrode-skin interface, and the ECG input amplifier are the principal sites where rectification occurs.

Demodulation of the RF in the amplifier of the new 78333A Monitor is suppressed by low-pass filtering all inputs (filter details are described in the main text). The filters also suppress interference from radio transmissions. As also described in the main text, a common-mode RF signal can be converted to a normal-mode signal by an imbalance in the capacitance-to-ground at the differential amplifier inputs. The capacitances-to-ground of all points in the floating input circuit in the new monitor are made equal by surrounding the circuits with a metal enclosure. The enclosure also shields the sensitive input circuit from radiated RF.

Body Rectifiers

Demodulation of the electrosurgery RF also takes place at the ECG electrodes, injecting the RF modulation into the ECG signal. An electrode with its electrolyte forms a rectifier with the skin.[1] The resulting voltage offset is proportional to the current passing through the electrode and it is inversely proportional to the frequency. For example, 1-mV offset is produced by 10 mA/cm² of 10-kHz current passing through a silver-silver chloride electrode whereas at 100 kHz, a 1-mV offset is produced by 60 mA/cm². RF filters, consisting of a 10-kΩ resistor and 3-mH choke in series with each electrode lead, reduce this current by factors between 4 and 8 to 1.

Another important source of interference is the scalpel-to-tissue interface. This interface acts as a lossy rectifier, generating a low-frequency voltage on the patient. In addition to the modulation placed on the RF by the electrosurgery machine, modulation arises from the scalpel-to-body arc, which varies with the surgical technique used. As the arc reaches its limit in length, it breaks and re-ignites at random frequencies, producing 100% modulation. This modulation is detected by the scalpel rectification process and coupled to the ECG electrodes and the monitor.

Tests have shown the interference generated by the scalpel rectification to be the same order of magnitude as interference generated by electrode rectification of the RF, the total interference being about 200 mV peak-to-peak for the 120-Hz modulation used for cutting and 800 mV peak-to-peak of noise between 0.1 and 5 kHz for the pulse modulation used during coagulation. Interference from the electrode rectification is suppressed by the RF filters in the electrode leads but the interference from the scalpel rectification is unaffected. Since no amount of filtering can reduce interference within the bandpass of the ECG amplifiers, operating procedures must be invoked to minimize this interference.

Minimizing Interference

First, use of an electrosurgery machine that has a capacitor in series with its output is helpful. Capacitors (typically 0.0022 μF) were used originally to eliminate muscle stimulation caused by frequency components below 120 Hz but they also attenuate low-frequency current flowing in the scalpel circuit, minimizing the low-frequency potential generated on the patient.

Secondly, placing the return plate as close as possible to the surgical site confines the electrosurgery current to a small area, reducing the low-frequency differential signal seen by the monitor. In addition, arranging the ECG electrodes with respect to the plate position so the ECG electrode vector is perpendicular to the scalpel current vector further reduces the interference seen by the monitor. For example, in an open-heart procedure the return plate should be on the patient's back in a vertical line directly under the incision, and the ECG electrodes should be in a horizontal plane on his chest.

Further, the ECG electrodes should be placed as far as possible from the surgical site and equidistant if the electrodes surround the site. A symmetrical placement of the electrodes causes low-frequency interference to be picked up as a common-mode signal that can be eliminated in the amplifier.

Burn Hazards

There is also a potential instrument-related hazard for the patient during electrosurgery: that of RF burns under the ECG monitoring electrodes. Burns can occur if the normal current return path of the electrosurgery machine is broken so the current flows to ground through the monitor. The 50-pF stray capacitance between a typical powerline-connected monitor's floating and grounded circuitry, which supplies a high degree of isolation at 60 Hz (>50 MΩ), becomes marginal at 1 MHz (3 kΩ).

If the electrosurgery machine fails to notice an interruption in the normal current return path, it will drive all its energy through the impedance of the body (about 500Ω), the electrode impedance (about 150Ω) and the stray capacitance between the monitor's isolated input circuit and ground (about 50 pF). At 2 MHz, a 1000-volt surgical drive would cause 160 mA RF current through each of the three ECG electrodes, each of which has a contact area of 1.5 cm² (the threshold for burns[2] has been determined to be 100 mA/cm² for 10 seconds). Burns from this source can be prevented in any monitor by inserting RF blocking impedances in series with the patient leads.

The RF blocking impedance should be placed as close as possible to the electrode sites and the cables themselves should be kept as far as possible from grounded objects, such as tables and other instruments, to minimize the capacitance to ground of the signal conductors.

Although electrical mishaps in the operating room are rare, the fact that they can occur is reason enough to take all measures possible to minimize potential injuries.

--Sherry R. Grobstein

References

1. T.C. Carr, A.L. Holt, and P.N. Katz, "Non-Linear Aspects of the Bioelectrode-Electrolyte Interface," First International Conference on Biomedical Electrode Technology, Stanford, California, September 1973.
2. C.M. Becker, I.V. Malhotra, J. Hedley-White, "The Distribution of Radio Frequency Current and Burns," Anesthesiology, Vol. 28, No. 2, February 1973.
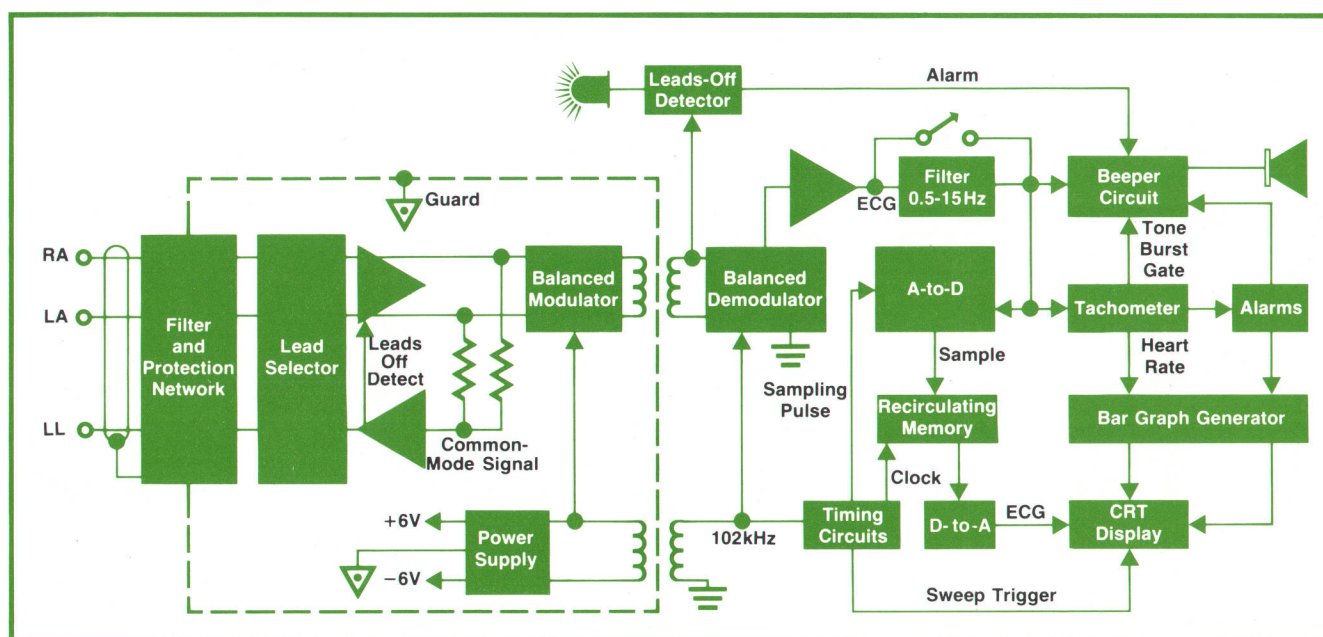
Fig. 2. *Simplified block diagram of the Model 78333A ECG Monitor. The input circuits are isolated from chassis ground for patient protection.*

The recirculating memory consists of eight 1024-stage shift registers operating at a clock rate of 250 kHz. The output of each shift register is fed back to its input so the contents of the shift registers recirculate continuously. Thus, a waveform acquired at a rate of 250 samples/second is output repetitively at a rate of 250,000 samples/second.

The samples are reconverted to an analog signal for presentation on the CRT display. CRT sweep time matches the time to read out 1024 samples so the contents of the memory, representing the most recent four seconds of the original ECG waveform, are traced in four milliseconds. The relatively fast repetition rate of the stored information causes the displayed waveform to appear bright with no fading.

Heart Rate Derivation

The original ECG waveform is also supplied to the tachometer circuit. This circuit has a one-shot multivibrator that generates a 185-ms pulse when triggered by the R wave, the major vertical excursion of the ECG waveform. The 185-ms pulses are averaged to derive a dc voltage proportional to heart rate. The heart-rate average is applied to one input of a comparator and the CRT horizontal sweep ramp to the other. When the two inputs are equal the comparator output resets a flip-flop that was set at the start of the sweep, thus generating a pulse that is used as an unblanking pulse for the CRT. This pulse unblanks the CRT while a low-amplitude, 64-kHz raster is applied to the vertical deflection system causing a widened horizontal line or bar to appear on the display. The length of the bar is proportional to heart rate.

The CRT displays two channels in an alternate-sweep mode. On one sweep, it presents the reconstructed ECG waveform. On the next sweep, it displays the heart-rate bar.

The 185-ms pulse generated in the tachometer is also sent to the beeper circuit where it gates an oscillator, generating a tone burst in response to each heart beat. The oscillator is frequency modulated by the ECG waveform so any change in the amplitude or shape of the ECG waveform causes a change in the characteristic sound of the beeper.

The "leads-off" detector circuit operates on the principle that loss of body contact on the part of either the RA or LA electrode causes a loss of bias at the corresponding amplifier input. The amplifier then saturates, causing the balanced modulator to output a maximum amplitude waveform. The waveform is rectified in the leads-off detector and applied to a comparator that switches on an alarm circuit (INOP) when the waveform exceeds a certain amplitude.

Loss of body contact in the LL circuit causes a loss of load in the reference-drive amplifier, and hence a change in output level that is coupled back to the input amplifier to cause it to saturate and trigger the leads-off detector.

Operation of the alarm limits is similar to the heart rate bar except that there are two comparators to sense when the heart rate goes beyond selected limits. A voltage representing a limit is applied to a comparator and the sweep ramp voltage is applied to the reference input. The outputs of the two comparators initiate blanking signals that gate a high-frequency raster that traces horizontal bars on the display. These
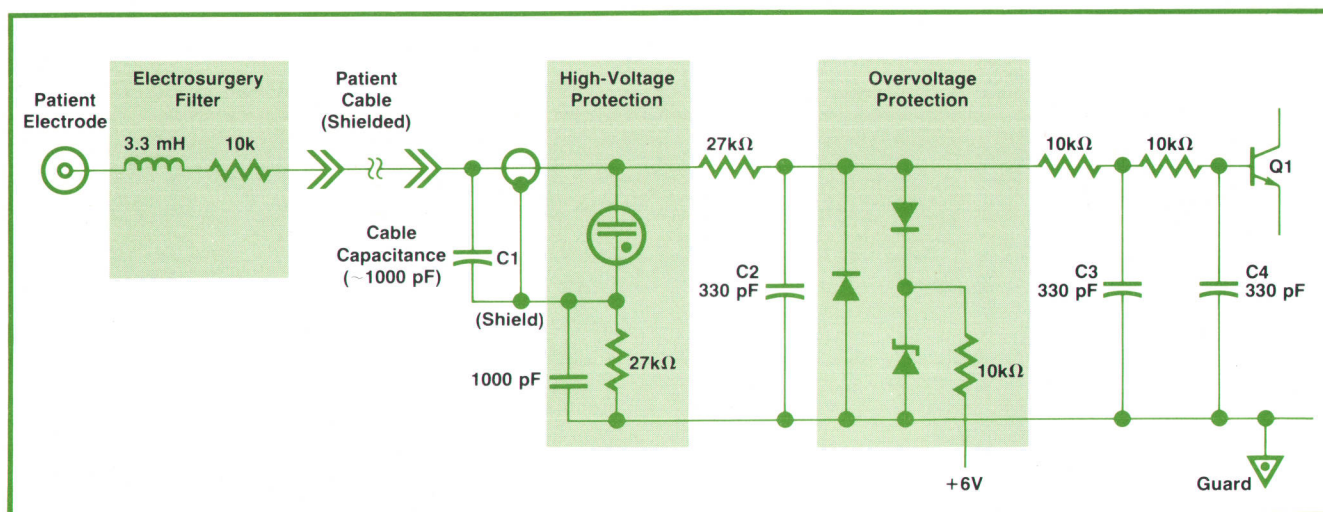
Fig. 3. *ECG input network includes low-pass filters, to suppress RF interference, and voltage clamps to prevent defibrillator pulses from damaging the sensitive input amplifier.*

show where the limits are set (see Fig. 1).

Logic circuits detect whether or not the heart-rate comparator triggers between the times that the two limit comparators trigger. If not, the alarm circuits are set.

The monitor can also display EEG waveforms. In this case, the gain of the amplifier chain is increased by 10 and the tachometer and related heart-rate circuits are disabled.

Input Filtering

As described in the box on page 28, filtering is required on the input leads to reduce interference caused by electrosurgery and radio-frequency emissions. To reduce the interference to acceptable levels, the ratio of amplifier sensitivities to the ECG signal (1 mV at less than 100 Hz) and to the electrosurgery machine (100V at 1 MHz or so) must be at least 10^5. The filter, however, must have a cutoff frequency above 10 kHz for adequate transient response of the reference drive* (the reference drive may be switched to any electrode in Model 78333A so the filters on all

*The reference drive electrode (left leg or LL) supplies an amplified and inverted signal derived from the common-mode signal, essentially including the patient in a negative feedback loop that increases the amplifier's common-mode rejection ratio. Current levels are quite low, however,—less than 100 nA.
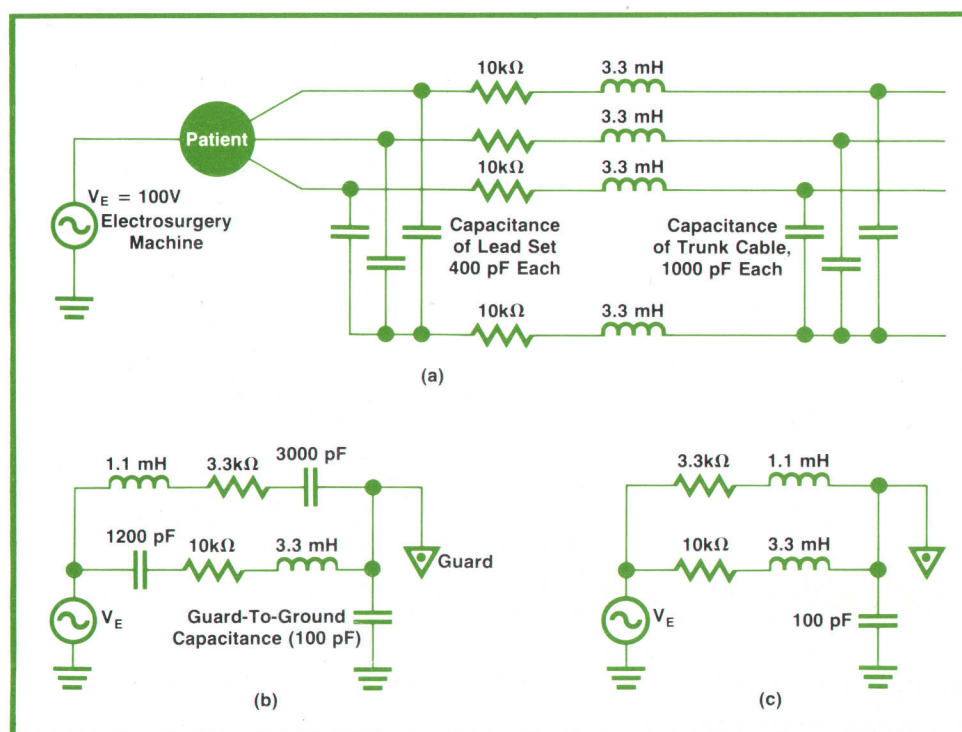

Fig. 4. *Equivalent network for the input cable (a) reduces to the network (b) which can be simplified to the network (c).*
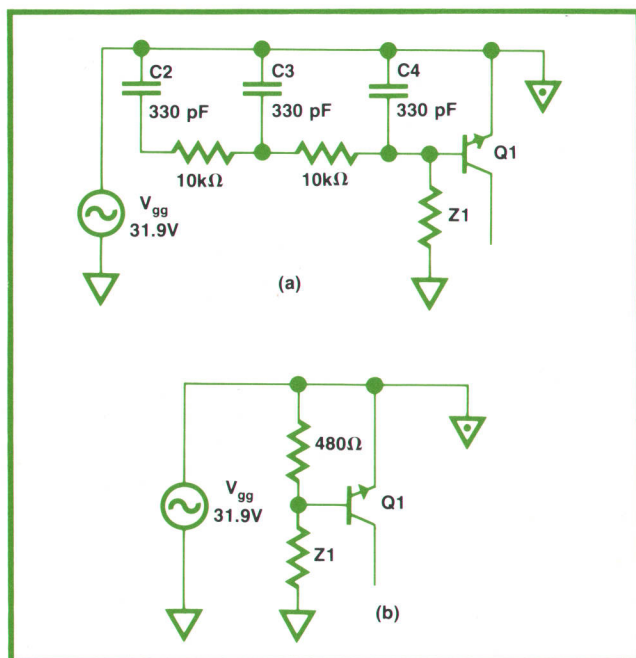
30

Fig. 5. *Diagram in (a) shows the network at one input of the ECG differential amplifier. Z1 represents the imbalance in stray capacitance at the amplifier inputs. V_{gg} is the voltage at the instrument input resulting from an interference potential at the patient electrodes.*

leads must have the 10-kHz bandwidth).

With the 10-kHz cut-off, a three-pole filter is needed to achieve a 10^5 reduction in signal level at 1 MHz. Five poles are used in the monitors, however, with three provided by RC filters within the instrument and two provided by the electrosurgery filters (10 kΩ and 3.3 mH) and the conductor-to-shield capacitance of the cable (1000 pF), as shown in the diagram of Fig. 3.

A three-pole filter with a cut-off of 15 Hz is provided at the output of the ECG amplifier (Fig. 2) to further reduce interference by some electrosurgery machines. If greater bandwidth is desired where this interference is not a problem, the filter can be bypassed.

The imbalance in capacitance from each input of the differential amplifier to ground poses another problem. This imbalance injects a differential RF signal that can be rectified and produce interference. The imbalance necessary to produce a 100-μV signal is surprisingly small.

Consider a situation where the electrosurgery machine causes a 100V RF signal to exist between the patient electrodes and earth ground. This will cause a voltage to exist between the input circuit guard and ground. This voltage is calculated as follows.

The network shown in Fig. 4a is a model for the electrosurgery filters and the capacitances of the electrode leads to the cable shield (which is connected to

the guard). This reduces to the network shown in Fig. 4b. At 1 MHz, the impedance of the 3000 pF capacitor (53Ω) is much less than 3.3 kΩ, and that of the 1200 pF capacitor (132 Ω) is much less than 10 kΩ, so these circuit elements may be ignored. The model then becomes like that in Fig. 4c. The guard-to-ground voltage V_{gg} is then:

$$V_{gg} = \frac{\frac{1}{j\omega\,(100\ \text{pF})}}{\frac{1}{j\omega\,(100\text{pF})} + \left[(3.3\text{k}\Omega + j\omega 1.1\text{mH}) \,||\, (10\text{k}\Omega + j\omega 3.3\text{mH})\right]} V_E$$

$$V_{gg} = 0.319\ V_E$$

With a V_E of 100V, V_{gg} is 31.9V. Using this value for V_{gg}, one side of the differential amplifier then looks like the network of Fig. 5a. The impedance Z1 represents the imbalance in the stray capacitance-to-ground of the input differential amplifier. Simplifying the network at 1 MHz gives the circuit of Fig. 5b. The value of Z1 that causes a base-emitter voltage of 100 μV at Q1 can now be found:

$$100\mu\text{V} = \frac{480\Omega}{|\text{Z1}| + 480\Omega}\,31.9\text{V}$$

$$|\text{Z1}| = 1.53 \times 10^8\Omega$$

which at 1 MHz is 0.001 pF.

Hence, the guard that shields the input circuits from electromagnetic radiation has an additional function: equalizing the capacitance-to-earth-ground of each amplifier input.

Sherry R. Grobstein
Originally from northern New Jersey, Sherry Grobstein joined Hewlett-Packard in 1972 in a work-study program with the Massachusetts Institute of Technology while pursuing BSEE and MSEE degrees. On getting her degrees in 1975, she went to work full time on the front-end circuits of the 78333A ECG Monitor, spending many hours analyzing the characteristics of electrosurgical interference. Sherry is a half owner of a 1946 Cessna 120 airplane and enjoys flying around the country to various air meets. In-between flights, she is kept busy renovating an 1840 house she recently purchased in nearby Lexington.

ABRIDGED SPECIFICATIONS
Model 78333A ECG Monitor
(UL Listed)

ECG AMPLIFIER SECTION

INPUT: Differential input. Protected against defibrillator and electrocautery potentials. Input impedance greater than 10 megohms below 50 Hz.

PATIENT ISOLATION FROM INSTRUMENT GROUND: ≥12 megohms minimum at 60 Hz.

CHASSIS LEAKAGE CURRENT TO GROUND (with power cord): Less than 30 μA at 115 Vac, 50-60 Hz; less than 60 μA at 230 Vac, 50-60 Hz.

COMMON MODE REJECTION WITH PATIENT CABLE: ≥106 dB at 50-60 Hz with 5k ohm imbalance.

NOISE: Less than 10 μV rms maximum referred to input with each lead connected to ground through shielded 25k ohm resistor.

ECG CALIBRATION SIGNAL ACCURACY: 1.0 mV ±2.5% referred to input at 25°C.

BASELINE RECOVERY TIME FOLLOWING DEFIBRILLATION: 1 second.

FREQUENCY RESPONSE (3 dB POINTS):

	Cathode-Ray Tube	System Output
Diagnostic	0.05 to 50 Hz @1 cm deflection	0.05 to 100 Hz (minimum)
Monitoring	0.5 to 50 Hz @1 cm deflection (typical)	0.5 to 50 Hz (typical)
ES Filter	0.5 to 15 Hz	0.5 to 15 Hz
EEG	0.7 to 40 Hz @1 cm deflection (typical)	0.7 to 50 Hz (typical)

LEAD SELECTION: Buffered lead selector with seven ECG positions, EEG, and STD positions. Can be used with three patient electrodes and retain leads I, II, and III. Automatic INSTO of ECG preamp occurs as setting of lead selector is changed.

PULSE AMPLIFIER SECTION

INPUT: Model 780-16 Ear Plethysmograph or Model 14301A Finger Plethysmograph connects to rear panel PLETH INPUT connector.

GAIN: Adjustable by rear panel PLETH GAIN control. Maximum gain 250.

CARDIOTACH: Cardiotach operates on displayed waveform in ECG modes. Range: 0 to 250 bpm on CRT; 0 to 3V output at system connector corresponding to 0 to 300 BPM.

ALARMS

DELAY: 5 seconds. Latching or non-latching alarms provided by internal switch (non-latching alarms, reset automatically when heart rate returns to limit range).

INOP LIGHT: Illuminates when leads-off condition is detected in ECG modes. When lit, alarms are disabled.

BEEPER: Audible QRS; pitch variation upon arrhythmia; alarm tone for INOP condition and out-of-limits heart rate.

DISPLAY

SWEEP SPEED: 25 or 50 mm/s ±5% corresponding to 4 or 2 seconds of display time respectively.

VERTICAL RESOLUTION: 8 bits, (256 levels).

DISPLAY AREA: 8 cm vertically by 10 cm horizontally. Upper 6 cm used for analog display; lower 2 cm used for cardiotach and alarm limit bargraphs.

REAR PANEL CONNECTORS AND CONTROLS:

DEFIBRILLATOR connector	QRS BEEP volume control
PLETH INPUT connector	ALARM VOLUME control
PLETH GAIN control	INTENSITY control
Two remote connectors for system input/output	LINE SELECTOR SWITCH: 115/230 Vac.

General

WEIGHT: 11.4 kg (25 lbs) with battery; 9.1 kg (20 lbs) without battery.

SIZE: 20.3 cm H × 34.93 cm W × 42.55 cm D (8 × 13¾ × 16¾ in).

POWER: 115/230 Vac, 50-60 Hz; +10%, −17%.

POWER CONSUMPTION: 15 VA normal use; 45 VA with instrument operating from line and battery undergoing recharge from fully discharged state.

BATTERY OPERATION TIME (battery new, fully charged): 6 hours.

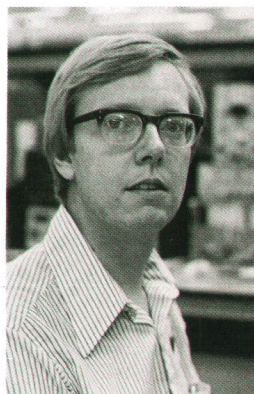**RECHARGE TIME FROM FULL DISCHARGE:** 16 hours.

OPERATING TEMPERATURE: 0°C to 55°C.

COLOR: Moss gray case, white front panel, smoke green display section.

PRICE IN U.S.A.: $3800 including shielded patient cable and disposable electrode sets.

MANUFACTURING DIVISION: WALTHAM DIVISION
175 Wyman Street
Waltham, Massachusetts 02154 U.S.A.

Ronald D. Gatzke

Ron Gatzke has been involved with ECG amplifiers and electrode systems ever since he joined HP in 1969, initially working on the 5600-series computerized ECG systems. Prior to HP, Ron designed radar systems. Ron earned a BSEE degree at Western Reserve University, Cleveland, Ohio, and an MSEE degree (1972) at Boston's Northeastern University. Ron enjoys camping and hiking with wife and daughter (9) and he's a student of the keyboard (piano, harpsichord, and an 1890-vintage organ at a church).

```
325757AAAA128MCANA01   153
MR  M L  MCANNALLY
#320
BOX # 12826
PENSACOLA                    FL   32575
```

CHANGE OF ADDRESS:
To change your address or delete your name from our mailing list please send us your old address label (it peels off). Send changes to Hewlett-Packard Journal, 1501 Page Mill Road, Palo Alto, California 94304 U.S.A. Allow 60 days.

HP Archive

This vintage Hewlett-Packard document was preserved and distributed by

www.hparchive.com

Please visit us on the web!

On-line curator: John Miles, KE5FX

jmiles@pop.net