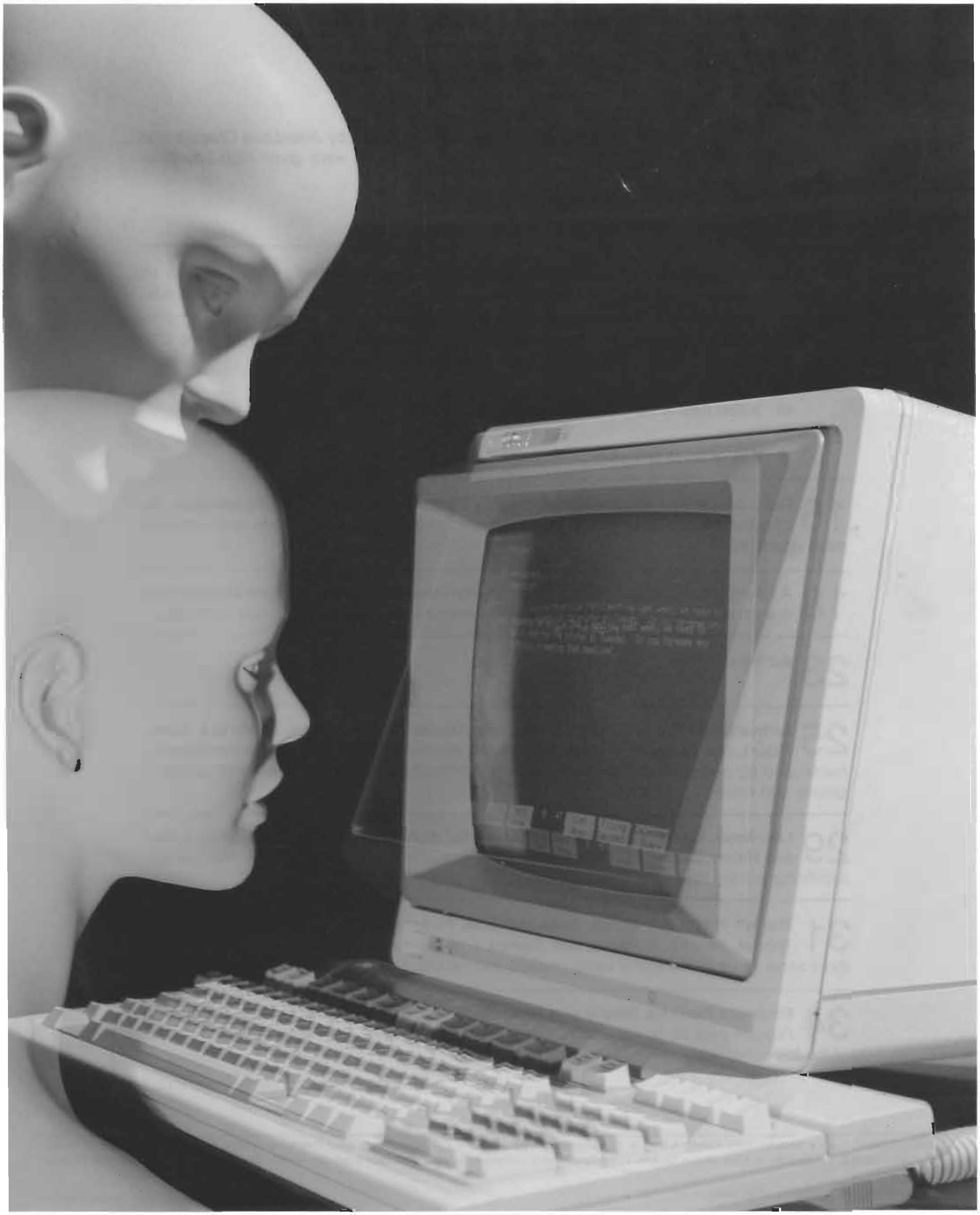
HEWLETT-PACKARD
JOURNAL

APRIL 1985



Authors

April 1985

4 Low-Cost Terminal

Jean-Louis Chapuis

Jean-Louis Chapuis is a section manager at HP's Grenoble Networks Division and has been at HP since 1978. He provided technical marketing support for the HP 263X family of printers and 264X family of terminals, was the designer of the HP 3074M Data Link Adapter, and was the project manager for the HP 2392A Terminal. Before coming to HP he was a researcher and teacher in an R&D lab for the French Air Force. Jean-Louis is a native of Rochefort, France and earned an electronic engineering degree from the École Supérieure d'Électricité in 1977. He lives in Meylan, France with his wife and two daughters and likes skiing, bicycling, and reading.

Michèle Prieur

Michèle Prieur came to HP in 1980, the same year she earned a degree in electronic engineering from the École Supérieure D'Électricité. She contributed to the development of the firmware for the HP 2392A and is now working on terminal emulation. She is interested in terminal firmware and application software for personal computers. Michèle was born in Lyon, France and is a resident of Grenoble, France. She is married and enjoys horseback riding.

8 Terminal Mechanical Design

Michel Cauzid

Michel Cauzid was born in Vouziers, France and received his diploma from the École Nationale Supérieure de Méchanique et Microtechniques in 1970. Before coming to HP in 1979, he taught mathematics in Africa as an alternative to French military service and worked in micromechanics. At HP he has been a mechanical designer for the HP 2333A Controller, the HP 3092 Terminal, and the HP 2392A. Michel's professional specialty is computer-aided design. He is a resident of Bresson, France, is married, has four sons, and enjoys hiking.

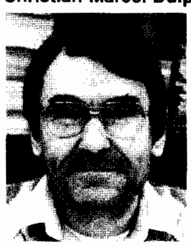
9 Terminal VLSI Design

Jean-Jacques Simon

Born in Metz, France, Jean-Jacques Simon studied electronics at the University of Nice, from which he received masters and doctoral degrees (1975 and 1978). At HP since 1977, he has contributed to hardware and firmware development of a number of terminal products, including the HP 3075A, 3077A, and 2642A. He was also the project leader for IC development for the HP 2392A Terminal and is coauthor of a patent on the HP Human Interface Loop. Jean-Jacques is married, has two children, and lives in Saint Egrève, France. He likes outdoor activities and rides his motorbike to work every day, even in the winter.

16 Automated Production

Christian-Marcel Dulphy



Christian-Marcel Dulphy was born in Tonnay-Charente, France and graduated in 1966 from the École Nationale Supérieure d'Électronique et de Radioélectricité de Grenoble. Before coming to HP in 1972 he served as a chief petty officer in the French Navy and worked as an electronics technician and as an R&D engineer. His HP experience has centered on engineering and management in production and manufacturing. He contributed to the development of the manufacturing process for the HP 2100 Computer and the HP 7905 Disc Drive. His professional interests include robotics and automation. Christian-Marcel is married, has three children, and lives in Saint-Egrève, France. When he is not involved in do-it-yourself projects, he enjoys cross-country skiing, hiking, gardening, and reading.

18 Terminal Analog Design

Jean-Yves Chatron

Jean-Yves Chatron joined HP's Grenoble Division in 1973, where he has worked as a production engineer, a service engineer, and as an R&D engineer. He contributed to the development of the HP Interface Bus for the HP 3075A Terminal and designed the power supply for the HP 2392A. A native of Nantes, France, he received an engineering degree from the Institut Universitaire de Technologie (1972) and served in the Army as a radio communicator. He now lives near Grenoble, is married and is the father of two sons and a daughter. Outside of work, he is interested in audio electronics.

René Martinelli

René Martinelli was born near Grenoble, France and received a master of science degree from the University of Grenoble (1969) and an electronic engineering degree from the University of Toulouse (1971). His experience before coming to HP in 1973 was in IC test design. At HP he has been a production engineer on the HP 2100 and HP 21MX series of computers, the supervisor of the local HP repair center, and an R&D engineer. He contributed to the design of the HP 307X family of terminals and was the project leader for the analog design of the HP 2392A Terminal. He lives with his wife and son in Eybens, France and likes amateur radio and skiing.

25 Intelligent Plotter

Martin L. Stone

Martin Stone received his BSME degree from the University of Texas at Austin in 1973 and came to HP's San Diego Division in the same year. He has been a manufacturing engineer and was an R&D engineer and project manager for the HP 7550A Plotter. A native of Dallas, Texas, he now lives in San Diego, California and enjoys backpacking, racquetball, golf, and playing his guitar.

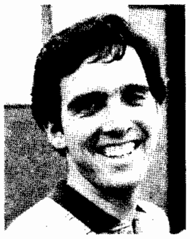
Todd L. Russell

Todd Russell is an R&D engineer at HP's San Diego Division. Since coming to HP in 1978 he has contributed to the design of plotter products, including the HP 7090A and the HP 7550A. Todd was born in Los Angeles, California and now lives in San Diego, California with his wife and son. He is a scoutmaster and commissioner for the Boy Scouts of America and is interested in camping, softball, tennis, and church activities.

Peter L. Ma

Peter Ma was born in Hong Kong and educated at the University of Washington (BSEE, 1978) and at Stanford University (MSEE, 1982). He joined HP in 1978 and designed the I/O processor system for the HP 7310A Printer and the digital circuits and gate arrays for the HP 7470A Plotter. He was the project leader for the electronic design of the HP 7550A and is now the section manager for manufacturing engineering. Peter lives in San Diego, California and is interested in tennis, skiing, water sports, and traveling. He is also an audio enthusiast.

Jeffery W. Groenke



A native of Minneapolis, Minnesota, Jeff Groenke attended the University of Minnesota (BSME, 1980) and San Diego State University (MSME, 1983). He has been at HP since 1980 and has worked as a manufacturing engineer and later as an R&D engineer for the HP 7550A. He is a member of the ASME and is continuing his engineering education at the University of California at San Diego. Jeff is a resident of San Diego, is married, and has a son. His outside interests include skiing, bicycling, sports cars, and spending time with his family.

29 Pen-Lift Mechanism

Hatem E. Mostafa

Hatem Mostafa is an R&D project leader at HP's San Diego Division. After joining HP in 1979, he designed the power supply for the HP 7580A Plotter. Later he designed the linear motor, the drive electronics, and the servo control system for the penlift for the HP 7550A. He is the coauthor of a November, 1981 HP Journal article on the HP 7580A. Hatem was born in Cairo, Egypt and received his BSEE degree from the University of Minnesota in 1979 and his MSEE degree from Stanford University in 1982. He lives in San Diego, California with his wife and loves the ocean. He enjoys scuba diving, body surfing, and walking on the beach.

Tammy V. Herr

At HP's San Diego Division since 1980, Tammy Herr has been a development engineer and mechanical designer. More recently she has worked as a regional sales engineer and sales development engineer. She is a native of San Diego, California and presently lives in Fallbrook, California with her husband. She likes skiing, bicycling, body surfing, sailing, and guitar playing.

31 X-Y Servo

David C. Tribolet

Born in Tucson, Arizona, Dave Tribolet was educated at the University of Arizona (BSME, 1978) and Stanford University (MSME, 1979 and MSEE, 1982). Since coming to HP in 1979 he has been a mechanical designer for the HP 7470A Graphics Plotter and a project leader for the HP 7550A Plotter. He is now an R&D project manager. He is the coauthor of an HP Journal article on the HP 7470A and is named as a coinventor on a patent on a bidirectional pen change mechanism. His work has also resulted in a patent application on a switchless pen sensor. Dave lives in San Diego, California, teaches a machine design course at the University of California at San Diego, and enjoys basketball and bicycling.

Thomas J. Halpenny

Author's biography appears elsewhere in this section.

Kenneth A. Regas

Ken Regas was born in San Diego, California, served in the U.S. Navy, and received a BA degree in management from Golden Gate University in 1976. He also studied at San Jose State University (BSME, 1980) and at Stanford University through the HP fellowship program (MSME, 1984). At HP since 1980, he contributed to the development of the HP 7550A and is now an R&D project leader. Ken is a resident of Poway, California, is married, has two children, and is interested in machine design and control.

34 Plotter Firmware

Thomas J. Halpenny

Tom Halpenny came to HP in 1974 and has worked on firmware development for a number of HP plotters, including the HP 7245A, HP 7221B, HP 7220A, and HP 7550A. He received his BS degree in engineering from Harvey Mudd College in 1973 and his MSEE degree from Stanford University in 1974, and is interested in computer programming and firmware development. A native of San Diego, California, Tom now lives in Escondido, California, is married and has a young daughter. He likes bicycling, video engineering, and reading books to his daughter.

An Intelligent Plotter for High-Throughput, Unattended Operation

This plotter quickly produces multiple copies of high-quality graphics output for use in presentations and reports. Its high throughput and automatic cut-sheet feeder make it useful for unattended operation in shared environments.

by Martin L. Stone, Peter L. Ma, Jeffery W. Groenke, and Todd L. Russell

THE EXPLOSION OF COMPUTER GRAPHICS in the business and technical environments has been intensified by the availability of products that generate hard-copy color graphics easily. Hewlett-Packard's pen plotters have made major contributions in this area, especially with the advent of microgrip plotting technology.[1,2] The application of this technology made HP plotters excellent high-performance, high-quality, low-cost solutions for both environments. There were features, however, that plotter customers were demanding, but that did not yet exist. These consisted of much greater throughput, unattended operation, more intelligence, and drafting plotter capabilities in an A/B-media-size machine. The addition of these features at a very low price while retaining the highest quality was paramount in the design of the HP 7550A Graphics Plotter (Fig. 1).

The HP 7550A is an eight-pen, A/B-size plotter with high quality and performance. Its increased throughput was achieved by developing high-performance servos to drive the pen and paper axes and the pen-lift mechanism. Placing the HP 7550A's microprocessor in all three servo loops, performing extensive servo modeling, and developing sophisticated control firmware were all key points in the resulting high-quality, high-performance, low-cost design. Plots done on the HP 7550A take less than half the time that they take on many other small-format plotters without sacrificing plot quality.

The customer's need to minimize time in handling pens and paper is answered by the HP 7550A's design. Thanks to the automatic cut-sheet feeder, the user no longer has to load plain paper or transparencies by hand, and the great inconvenience of tearing off sprocket holes or separating plots along perforations is eliminated. The design of the pen-lift mechanism contributes to lengthening the life of

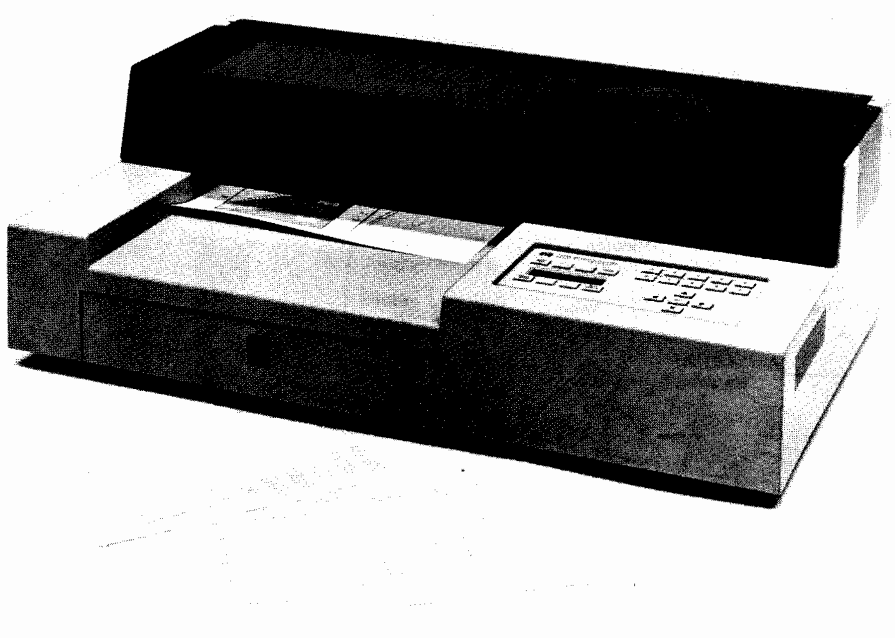


Fig. 1. *The HP 7550A 8-Pen Graphics Plotter is designed for high-throughput, unattended operation. These features allow the preparation of multiple copies of high-quality computer graphics, automated output of single charts for process monitoring, or use as a central graphics server.*

the pen by carefully controlling the velocity of the pen as it hits the paper. These features make the HP 7550A an excellent choice as a central source of hard-copy graphics, or for automatic test and process control systems.

Ease of use, or friendliness, comes from the extensive firmware features included in the HP 7550A. One key contribution is the internal, 12K-byte, user-definable graphics memory. This memory space can be allocated for five different functions: I/O buffer, vector buffer, replot buffer, space for polygon fill definition, and downloadable character space.

Two of the most powerful features are the replot and polygon fill capabilities. The replot buffer enables the user to store an entire plot in the HP 7550A and then reproduce it up to 99 times. Now the user can give a presentation using transparencies plotted by the HP 7550A and give the audience personal copies of the same information produced quickly and easily on paper. The polygon (area) fill capability is a real time-saving benefit in user programming and plotting time. Instead of programming a plotter to move stroke by stroke (many, many instructions) to fill a complex solid or crosshatched area, all the user must do is invoke two or three HP-GL (Hewlett-Packard Graphics Language) commands to define a polygon and a fill type. From this information, the HP 7550A automatically figures out the required number and pattern of strokes.

Another contribution is the 32-character liquid-crystal display on the front panel. This display, coupled with the keyboard design, gives the user a simple menu-driven front panel that is easy to operate. Also, with the use of an internal nonvolatile memory, the customer can completely configure the HP 7550A in an RS-232-C/V.24 or HP-IB (IEEE 488) environment through the front panel, thus eliminating bothersome rear-panel switches.

The final major customer need addressed by the HP 7550A is for a plotter for the low-cost CAD/CAM systems available today. Users of these systems want a quality A/B-size drafting plotter with a price in agreement with the rest of their system. The HP 7550A is designed to use both polyester film and vellum paper, and liquid-ink as well as roller-ball pens. The high throughput of this plotter makes it a very good solution for producing check plots quickly, and its drafting-quality output produces excellent final drawings.

Mechanical Design

The mechanical design of the HP 7550A is characterized by the widespread use of plastic molded parts. This low-cost design approach was taken while still keeping quality and reliability as the top objectives. Many parts are designed to serve several purposes.

- Pen carriage:
  - Actuates a cam that lifts the pinch wheels for paper loading.
  - Actuates a cam to uncap pens during pen picks.
- Pen-lift mechanism:
  - Opens access door to platen surface to begin automatic paper-load sequence.
  - Senses paper during paper loading.
- Carousel sensing pair:
  - Detects presence, type, and positions of pens in carousel.
  - Detects up/down position of plotter window.

The key mechanical designs are highlighted in the articles on pages 29 and 31.

Electronic Design

The objective of the electronic design was to develop a cost-effective means of providing a high level of functionality and many enhanced features. For instance, one main printed circuit board contains nearly all of the electronic circuits, leaving only a small portion on the servo motor's optical encoder board and the pen-lift's encoder board. More functions and higher performance can be found on the one main board than are on seven separate boards from an earlier HP plotter. Several design philosophies helped achieve this, such as replacing analog circuitry with digital circuitry whenever possible, using large-scale integration (LSI), eliminating the need for any adjustments, and performing many functions with the same components.

The single 68000 microprocessor controls every movement in the servo motors and pen-lift mechanism from commands received through the HP-IB or RS-232-C interface. It services the front panel and rotates the carousel

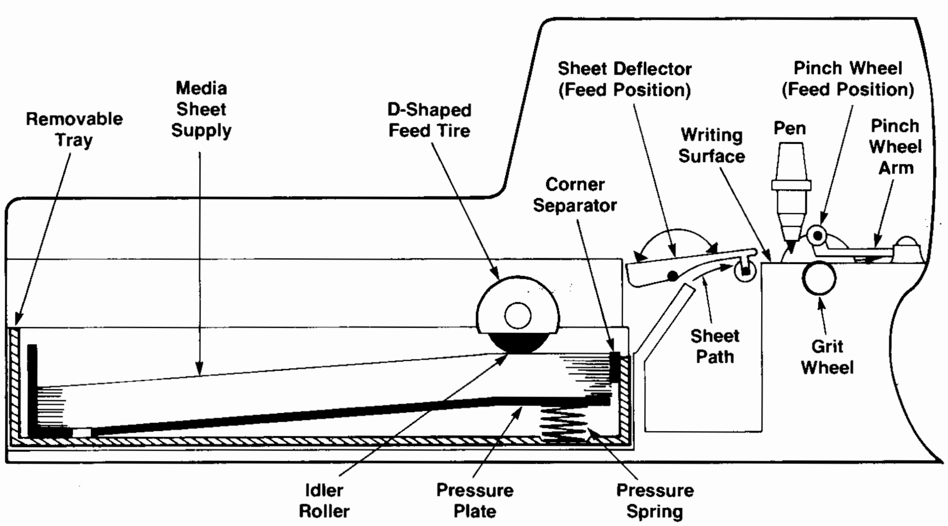


Fig. 2. *The HP 7550A Plotter's sheet-feed mechanism is similar to that of a photocopier, but with much higher alignment accuracy. It can feed up to 150 sheets without reloading.*

and paper-feed step motors. It also participates in measuring the unregulated power supply voltage for the servo motors by successive approximation. The task of continuously pulsing the LED (light-emitting diode) in the carousel detector is performed entirely by the microprocessor, rather than by a separate timer circuit.

The digital electronics section is greatly simplified by the use of the 68000 microprocessor and two custom standard-cell ICs manufactured at HP's Cupertino Integrated Circuits Operation. The microprocessor's strong output drive capabilities and the use of high-density ROMs and RAMs eliminate the need for any costly address or data bus buffering. The two custom 40-pin NMOS ICs contribute to significant cost savings by replacing more than 80 small-to-medium-scale ICs. Overall, the digital section is mostly made up of a handful of LSI components, reaping the benefits of increased reliability and reduced board space and power consumption.

The power supply portion of the electronics offered some interesting challenges. The servo motors require a power supply with very high (greater than 300 watts) peak power capabilities to produce the desired accelerations and decelerations. Since servo performance depends on the supply voltage, a costly regulated design would seem necessary. However, by not regulating the voltage, but instead measuring the value and compensating the servo operating parameters in firmware by using the microprocessor, optimum performance can be maintained. To help keep the power supply simple, a single switching circuit provides three regulated voltages—a tightly controlled 5-volt output along with two adequately controlled 12-volt outputs. The switching circuit takes advantage of a sophisticated IC regulator and employs a switching element that gives three outputs rather than just one. The result is a much reduced parts count and improved efficiency and reliability.

Unattended Media Handling

Unattended operation requires that a plotter be able to supply a new sheet of plotting media without user intervention. Most plotters that feature automatic media handling use a system that supplies the media from a rolled or fanfold format. It was decided early in its design that these formats were unacceptable for the HP 7550A's intended market. These formats require special paper which is more expensive. To change the media type, the user must go through a time-consuming sequence of removing and changing the supply and getting the new media started in the feed system.

Hence, the decision was made to design this new plotter with an integral system for feeding precut stacks of sheet media. The system requirements were that it be able to remove individual sheets from a supply stack, deliver each to the writing area, and align each sheet with the pen axis within two-tenths of a degree. Also, it had to eject and stack completed plots automatically and provide capabilities for feeding ANSI A and B and ISO A3 and A4 papers, as well as A and A4 transparency film. The system had to be very reliable, yet provide easy access if a feed failure should occur. In addition, the ability to load single sheets manually was required.

The cut-sheet feeding system for the HP 7550A uses a forward buckling technique for separating the top sheet from the supply stack (Fig. 2). This technique, commonly seen on inexpensive photocopiers, was selected because of its low cost and high reliability. The stack of sheets is first placed in a removable tray in which are mounted two corner separators, one at either side of the forward edge of the stack. These separators allow the feed tires to buckle an individual sheet off the top of the stack. The stack is pressed up against the feed rollers by two compression springs under a hinged plate, which is located in the tray directly beneath the stack. Two different trays are available. One comes with the instrument and can be adjusted easily for A or A4 media sizes. The other is an inexpensive option and can be adjusted easily for B or A3 media.

A significant contribution of the sheet feeder is the design of the feed shaft system. Conventional feed systems use two rubber tires mounted to the feed shaft by one-way mechanical clutches and forced down on the stack, requiring an elaborate mechanism to relieve the tension springs when the user desires to insert or remove the tray. The HP 7550A uses a specially designed feed tire which has a flat cut on one side, giving it the shape of a D. When the flat side is lined up parallel with the surface of the top sheet, there is no contact, and the tray can be removed easily without the need for any complex release mechanisms. A key element of this system is that the HP 7550A's microprocessor must be able to determine the orientation of the feed shaft, so the flats can be positioned parallel to the media when a sheet is not being fed. To do this, a very simple encoder was designed, consisting of a molded plastic gear with a narrow slit and an LED emitter-detector pair. This gear runs off the same gear the step motor uses to drive the shaft. The gear is keyed to the shaft orientation and passes between the emitter-detector pair. When the slit passes in front of the emitter, the receiver generates a signal that indicates to the processor that the shaft is aligned, and the feed cycle is complete.

Once the sheet has been pushed from the tray, it strikes

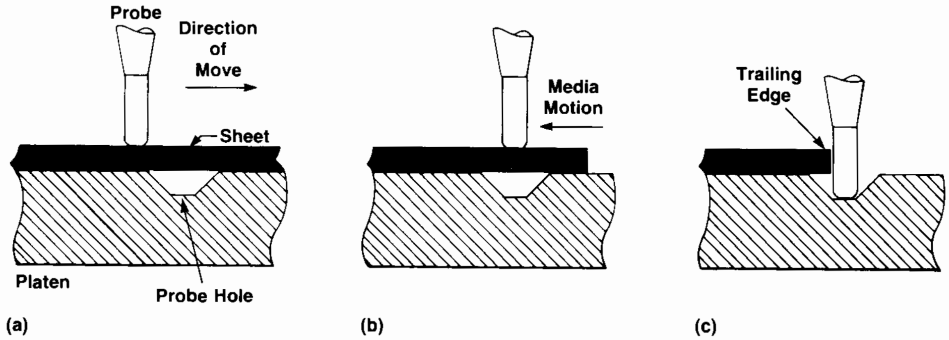


Fig. 3. *Edge sensing. (a) A probe on the Z carriage bottoms on the media. (b) The Y carriage moves the probe over a hole in the platen. (c) As the trailing edge of the sheet passes, the probe drops into the hole.*

a ramped surface, which directs it upward into a deflector. This deflector can be rotated open by motion of the Z carriage (pen-lift mechanism) to direct the sheet onto the platen. The pinch wheels are raised by engaging the Y carriage (pen-holder carriage) with a rotating cam. The sheet is fed until the D-shaped feed tires have completed a full revolution, passing the leading edge of the sheet under the raised pinch wheels. The Y carriage then disengages the cam, lowering the pinch wheels and grabbing the sheet between the pinch and grit wheels. Then, the sheet is ready to be pulled from the tray with the X-axis drive motor.

Edge sensing is done with the Z carriage. The Y carriage is moved over the platen and the pen holder is lowered. Since there is no pen in the holder at this time, lowering continues until a probe bottoms on the sheet on the platen surface (Fig. 3a). The position is read from the Z-carriage linear encoder and recorded. The platen height (including media thickness) is now known. The Y carriage then makes a short move, dragging the probe across the sheet until it is over a hole in the platen. Now the sheet is pulled from the tray (Fig. 3b). As the trailing edge passes, the probe drops to the bottom of the hole, signaling the end of the sheet (Fig. 3c). The paper length (A/A4 or B/A3) can be determined by reading how long the sheet was pulled before the trailing edge was detected.

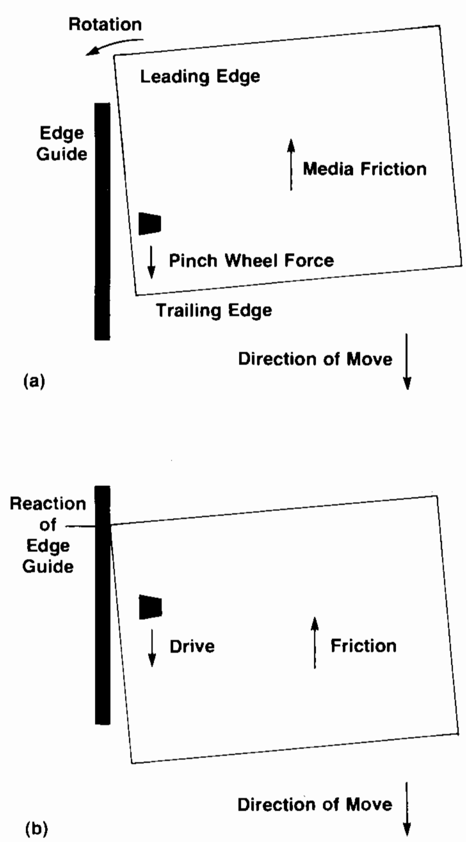


Fig. 4. *Sheet alignment. (a) As the first move begins, the sheet rotates about the left pinch/grit wheel combination and toward the edge guide. (b) As the move continues, the edge under the left pinch/grit wheel combination approaches the guide. Then a move in the reverse direction completes the alignment of the sheet against the guide.*

Once the entire sheet is on the platen, the alignment sequence starts by raising the right pinch wheel, leaving only the left pinch wheel engaged. The sheet is then driven back and forth twice. Initially the sheet is completely away from the left guide. As the first move begins, a mechanical couple is set up between the driving left grit wheel on one hand and the media's friction against the platen surface (Fig. 4a) and its inertia on the other. This causes the sheet to rotate about the left grit wheel and swing in against the edge guide. A stop above this guide keeps the sheet from climbing up and over it. As the move continues, the media edge under the left pinch wheel approaches the edge guide (Fig. 4b). The left grit wheel direction is then reversed, causing the trailing edge to move completely against the guide. After two more passes, the sheet is firmly aligned to the guide.

The final tasks are to find the trailing edge accurately (it is roughly known already) and to determine whether ISO or ANSI standard media is being used. The trailing edge is found as before. To determine which standard is used, the sheet width must be measured. The position of the left edge is now known to be at the edge guide. Only the right edge need be found to calculate the sheet width. The procedure is similar to that for finding the trailing edge. The Y carriage is moved to the right side of the platen over a slot (underneath and perpendicular to the right edge of the sheet) and inside the edge of an ANSI sheet, which is the narrower of the two (11 inches versus 297 mm). The probe is lowered until it bottoms on the sheet. The Y carriage is then moved enough to the right to be beyond an ANSI sheet edge. If the probe drops into the slot, the size is known to be ANSI. Otherwise, it is assumed to be ISO. The plotting area is now set.

After plotting, the sheet is unloaded on command by ejecting it past the grit wheels, stacking it in a catch tray placed behind the plotter. A new sheet is then automatically loaded, aligned, and ready for plotting.

Acknowledgments

The success of the HP 7550A was due to the great efforts of many people. Product design was done by Dick Kemplin and Lynn Palmer. The project benefited from the early leadership of Neal Martini, as well as continued support from Peggy Wyman and John Page. Bill Royce had the responsibility for the power supply and motor drive circuits and for meeting product electromagnetic-compatibility goals. Dave Ellement and John Wickeraad were involved in designing the custom ICs and the digital circuits.

Special thanks to Wally Halliday for the initial sheet feeding mechanism, Mark Majette for the media drive axis, and Kevin Bockman for the unloading design.

We could not have been successful without the extensive efforts of our manufacturing team: Juergen Przyllas, John Morton, Steve Lorenc, Rich Mandle, Marv Kozai, Otto Hirr, Dave Kelly, and Tim Holscher. And we give special thanks for the support and guidance of Norm Johnson.

References

1. W.D. Baron, et al, "Development of a High-Performance, Low-Mass, Low-Inertia Plotting Technology," *Hewlett-Packard Journal*, Vol. 32, no. 10, October 1981.
2. M.L. Patterson and G.W. Lynch, "Development of a Large Drafting Plotter," *Hewlett-Packard Journal*, Vol. 32, no. 11, November 1981.

Low-Mass, Low-Cost Pen-Lift Mechanism for High-Speed Plotting

by Tammy V. Herr and Hatem E. Mostafa

THE PEN-LIFT MECHANISM in the HP 7550A Plotter was designed to minimize manufacturing cost and to minimize the overall mass of the pen carriage assembly while meeting performance criteria of reducing cycle time (pen down and pen up) and providing variable writing forces for various pen types.

Mechanics

The pen-lift assembly (Fig. 1) consists largely of inexpensive injection-molded plastic parts. Every element of the vertically moving assembly attaches to a complex and highly critical part, the pen holder. The most severe operating condition imposed on this holder is during pen exchange, when several pounds of force are exerted on the pen pawl during sliding contact with the HP 7550A's 8-pen carousel. To supply the strength and lubricity necessary to survive pen exchange, the pen holder is molded of polycarbonate filled with 30% glass and 15% Teflon.™

Miniature radial ball bearings mounted on the pen holder constrain the assembly to the desired vertical motion. Dynamic modeling was performed to determine the optimal combination of bearing geometry and preload required to sustain the imposed loads while inducing no frictional forces greater than 3 gm.

Actuation for vertical travel and pen-down force is provided by a highly efficient linear motor. A coil-wound bobbin is electromagnetically translated over a pole cap and magnet column located inside a voice-coil cup. Energizing this coil with an electric current produces a vertical force proportional to the input current. An inexpensive insulation-displacement connector terminates the bobbin coil wire, eliminating a soldering operation. This magnetic assembly weighs only 40 grams and delivers 122 grams of force per root watt of power dissipation.

Because of the accumulation of tolerances, the distance between the pen nib and the platen surface can vary from 1.5 to 4 mm. Therefore, the geometry of the voice-coil cup is optimized for minimizing leakage flux, thus providing a constant force over the entire 4-mm working range of the pen-lift assembly. An optical encoder senses the vertical position of the pen-lift assembly to within 0.05 mm. The use of digital feedback eliminates the offset and drift problems inherent in traditional analog feedback systems.

Control

The pen-lift control system provides the minimum pen up/down cycle time while reducing pen impact momentum to maximize pen nib life. The control system's complexity is reduced and its reliability is greatly enhanced by incorporating the plotter's microprocessor into it. For any given control mode, the microprocessor can determine the position and velocity of the pen by reading an encoder register. Using the proper algorithm, the processor outputs two pulse-width-modulated signals to the pen-lift driver (see Fig. 2). The front end of the pen-lift driver performs a differential digital-to-analog conversion on the two control

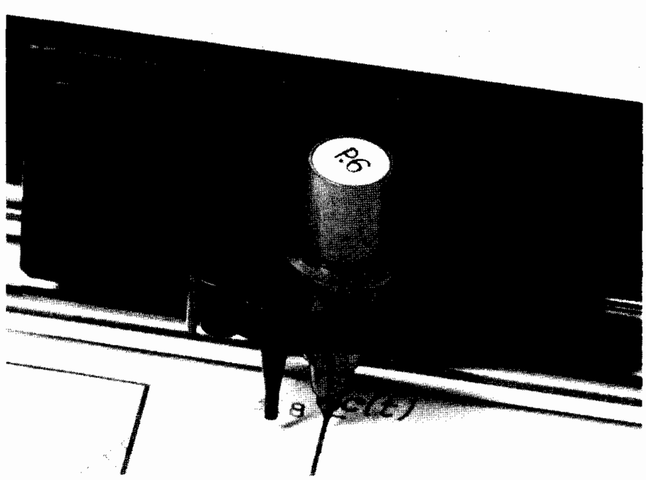


Fig. 1. *The pen-lift mechanism used in the HP 7550A Plotter is based on an electromagnetic voice-coil actuator and the use of the plotter's microprocessor to control pen drop velocity.*

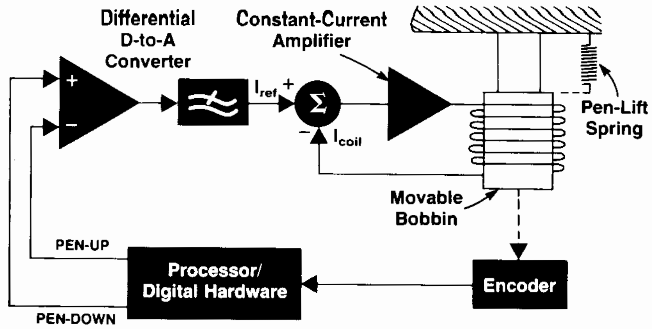


Fig. 2. *Block diagram of pen-lift control system.*

signals and the resulting single-ended analog signal is fed into a constant-current amplifier. The amplifier then drives the electromagnetic actuator appropriately.

The control system operates in four modes: pen down, fast drop, slow drop, and de-energized. In pen-down mode the system operates as a constant-force servo. That is, a constant force is applied to the pen nib against the plotting surface independent of vertical pen position. The writing force is chosen by the microprocessor from a set of eight values, depending on pen type. When a pen-up command is encountered in pen-down mode, the control system switches to a position servo and raises the pen 1.5 mm above the platen. The control system is now in fast-drop mode. The actual pen-up move requires no delay before lateral movement with the pen can begin. As long as lateral pen-up moves remain within a 2.5-cm radius from the location of the last pen-up command, the system continues to operate in fast-drop mode.

Because platen irregularities over a 2.5-cm lateral distance are considered to be minor, the pen height is considered to be known within a tight tolerance. Given a

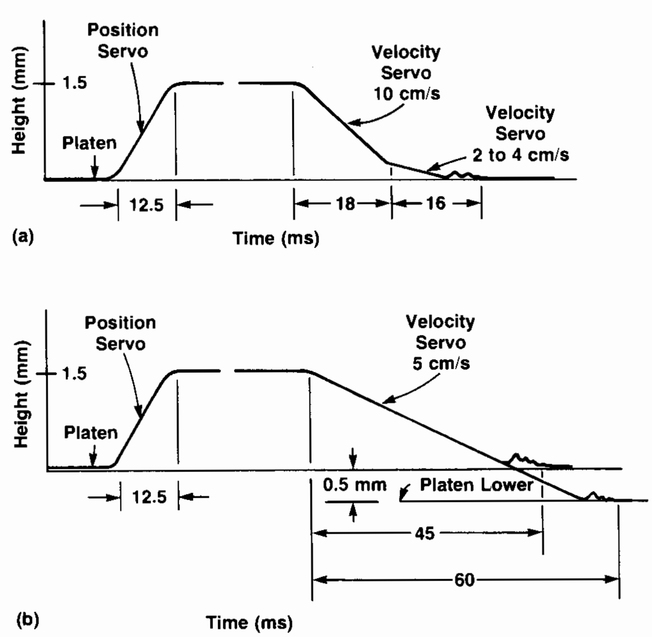


Fig. 3. *Pen height versus time for (a) fast-drop mode and (b) slow-drop mode.*

known pen height, the control system can execute a pen-down command very quickly. The pen-down move is accomplished in this case by switching the control system from a position to a velocity servo and then commanding the pen to descend at a high velocity. Slightly before impact, the control system significantly decreases the pen's downward velocity, thereby greatly reducing the impact momentum as the pen nib strikes the plotting media (see Fig. 3a). The final impact velocity is selected by the microprocessor as a function of pen type. This dual velocity approach makes it possible to lower the pen at a high speed, while independently selecting the optimum impact velocity for various pen and media combinations to reduce pen bounce and increase pen-nib life. The result is a pen-down delay of only 34 ms.

If, on the other hand, a lateral move greater than 2.5 cm occurs while the control system is in fast-drop mode, no assumptions about the distance of the pen from the platen can be made accurately enough. Therefore, the control system switches to slow-drop mode. When a pen-down command is executed in this mode, a slow velocity must be used during the entire pen descent until the pen contacts the platen. The pen-down delay in this mode can be as long as 60 ms (see Fig. 3b).

When a pen is picked from the 8-pen carousel, the pen-lift control system is in de-energized mode. In this mode, the mechanism is held at its topmost position by the pen-lift spring. It is in this initial state that the control system adaptively compensates for all offsets present in the system. These offsets include variations in the actuator force constant, pen-lift spring holding force and spring constant, and current driver offsets. The compensation is accomplished by using the constant-force servo to maintain the pen at an equilibrium position very near the platen. The force generated by the servo is exactly the amount needed to null all constant offsets in the system. A second force component that is proportional to pen position is also generated. This position-dependent force compensates for the effects of the pen-lift spring force constant. The overall offset nulling force is now added to all command forces generated in the different pen-lift operating modes. The elimination of any adjustment procedures on the manufacturing line makes the pen-lift mechanism a cost-effective, highly reliable system.

Acknowledgment

Special acknowledgment is extended to Chuong Ta for his excellent mechanical design contributions to the pen lift.

The HP 7550A X-Y Servo: State-of-the-Art Performance on a Budget

by David C. Tribolet, Kenneth A. Regas, and Thomas J. Halpenny

THE HP 7550A GRAPHICS PLOTTER features 6g acceleration along a vector, a maximum speed of 80 cm/s, repeatability of 0.1 mm with a given pen, and line quality comparable to the HP 7580 family of drafting plotters. At present, this represents the state of the art in plotter performance. The HP 7550A plotting mechanism uses two rare-earth magnet dc motors, each equipped with an optical encoder. Each motor drives one of two axes: the paper axis (X) or the pen axis (Y).

Both servo loops are closed in the HP 7550A's microprocessor using position and velocity feedback. Velocity feedback is provided not by a tachometer, but rather by using an estimate of the velocity derived from the encoder position information (Fig. 1).

The encoder positions for the X and Y axes are maintained in separate 8-bit registers. These 8-bit registers overflow every 256 counts (equal to a distance of 1.6 mm), but that is not a problem since the servo works with incremental encoder values. As long as the encoder register value changes by less than ±128 counts between samples, the servo can maintain its position with 8 bits. As it happens, the position changes only by a maximum of 38 counts between 300-microsecond samples, but 8 bits is a convenient size for the HP 7550A's microprocessor.

The servo motor control calculation during encoder sample n is:

$$M_n = (R_n - X_n) - [K_v/(K_pT)](X_n - X_{n-1}) \qquad (1)$$

The challenge is to convert this expression to "incremental" form, that is, to a function of $X_n - X_{n-1}$. To do this, the following definitions are necessary:

- The position error, where you want to be minus where you are, is defined to be $E_n = R_n - X_n$
- The "reference generator," which moves the reference R_n between encoder samples, computes increments in the reference which we call the reference velocity $V_n = R_n - R_{n-1}$.

Using these definitions, we have:

$$M_n = V_n + E_{n-1} - [1+K_v/(K_pT)](X_n - X_{n-1}) \qquad (2)$$

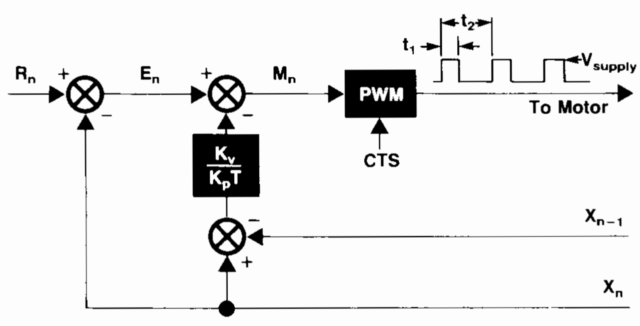
Note that each term on the righthand side of this equation is a small difference between two potentially large numbers, and hence amenable to 8-bit computations. Also note that the existence of position error E_n does not necessarily indicate failure to plot on the reference trajectory. The tracking servos are designed to lag the reference at any nonzero velocity. This lag is produced by velocity feedback in the control loop. By matching the dynamic response of the two servos, we ensure that position errors on the two axes are proportional to their respective reference velocities, placing the actual pen position on the reference trajectory (see Fig. 2).

The factor $1+K_v/(K_pT)$ is a constant, so the multiplication of $X_n - X_{n-1}$ by this factor is implemented by a "hard-coded" multiply. For example, if $1+K_v/(K_pT) = 8$, then the quantity $X_n - X_{n-1}$ is simply shifted left by 3 bits. The reference generator moves the X-axis and Y-axis references from one point to the next. The reference for each axis is accelerated to a maximum speed, maintained at that speed for a time, and finally decelerated near the endpoint. Since a straight line is always drawn from one point to the next, the ratio of Y-axis to X-axis reference velocities equals the slope of the line (see Fig. 3).

To conserve processor time, a new pair of X-axis and Y-axis reference velocities is computed once every four servo samples (1.2 ms), rather than every sample. The minimum addressable unit (one plotter unit, or P.U.) equals 0.025 mm (approximately 0.001 inch). Since there are exactly four encoder counts per P.U., the reference velocity is computed in P.U. per 1.2 ms, and the result V_n is sent to the servo (which expects reference increments in encoder counts) four times during the next four servo interrupts. This is a convenient way to convert from P.U. to encoder counts.

Curvy Servo Algorithm

The curved-line reference generator enables the HP



K_p = Position Gain (volts/count) = V_{supply}/CTS
K_v = Velocity Gain (volt-second/count)
X_n = Encoder Position at nth Interrupt (count)
R_n = Reference Position at nth Interrupt (count)
T = Servo Period (seconds)
E_n = Position Error at nth Interrupt (counts)
M_n = Motor Control at nth Interrupt (counts)
CTS = Counts to Saturation (counts)
t_1 = $K \times M_n$
t_2 = $K \times$ CTS
K = 0.5 μs/count
V_{supply} = Unregulated Supply Voltage

Fig. 1. *HP 7550A servo diagram.*

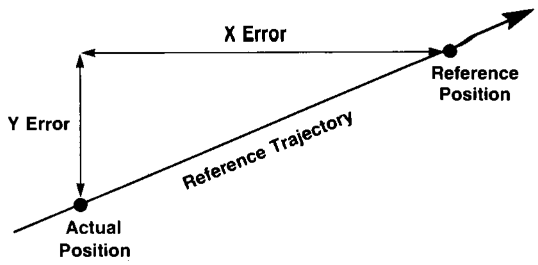


Fig. 2. *Matching the dynamic response of the two servos places the actual pen position on the reference trajectory.*

7550A to maximize line quality by drawing continuous curves without stopping at intermediate points. All curves are drawn as a sequence of short line-segment vectors, each having a slope slightly different from the previous one. Most plotters begin and end a vector at rest, with a reference velocity equal to zero. This is the easiest to implement because the reference generator needs to have no knowledge of previous or future vectors in a sequence. However, the HP 7550A's curved-line generator looks into the future by collecting a group of vectors into a first-in, first-out queue called the vector buffer. It usually takes longer to collect the vectors of a curve than it takes to plot them, so collecting vectors early before plotting prevents loss of throughput. A collection of vectors is released for plotting when either a pen-up command is received, the vector buffer becomes filled, or a certain amount of time has elapsed since the last vector was received by the vector buffer while the previous vector is plotting.

Fig. 4 shows how collected vectors become active. The vector buffer has a head pointer, from which vector information is taken to draw lines. It also has an active tail pointer and a virtual tail pointer. Vectors are added to the buffer at the virtual tail pointer. The vectors between the head and active tail pointers are those currently being plotted, while those between the active tail and virtual tail pointers are the vectors being collected. Collected vectors are released to be plotted simply by changing the active tail pointer to equal the virtual tail pointer.

Referring to Fig. 5, as the pen nears the end of vector 1 at point P, it slows to a maximum turning speed, which depends on the turning angle A. The smaller the turning angle, the larger the maximum turning speed can be. If the turning angle is large, then the turning speed reduces to zero. The actual turning speed also depends on the length of succeeding vectors. For example, suppose that a curve only has two vectors, the turning angle is 0 degrees, and the length of vector 2 is very small, say one plotter unit (see Fig. 6). Then the actual turning speed between vectors 1 and 2 is almost zero, since the plotter must stop at the end of vector 2 anyway.

When the curved-line generator is activated, it controls all vectors generated internally by the HP 7550A, as well as the vectors generated externally by the user. The plotter therefore performs the same curving action whether a circle is generated internally with the HP-GL circle instruction CI, or externally with the user computing each of the chord segments and sending them to the plotter.

The curved-line generator is one of two software-selectable reference generators. It has a fixed acceleration of 3.5g along the longer axis of a vector, while the conventional reference generator allows from 1 to 6g acceleration along the vector.

Vector Buffer

The vector buffer can also be used to increase plotting throughput for both reference generators. There is a critical vector length, approximately 100 P.U., below which the HP 7550A takes longer to prepare the vector for plotting than it actually takes to plot it. Without the vector buffer, the pen must sit idle for a time while the controller sends the vector to the plotter. Most plots have a mix of long and short vectors and pen-lift operations. With the vector buffer, the HP 7550A is able to prepare several vectors ahead of time while it is plotting a long vector or doing a pen lift so that, when the short vectors come along, there will be much less idle plotting time. Hence, throughput is significantly enhanced.

Cost-saving Strategies

To extract the best possible performance from the X and Y servos at minimum cost, several strategies are used. First, design solutions from existing product lines were borrowed for the HP 7550A, saving engineering manpower for the task of optimizing these technologies. The dc servo motor used in the HP 7580 family of drafting plotters is unsurpassed in the marketplace for performance at a low price, so we decided to build our machine around it, matching mechanism and drive electronics to its capabilities. Particular attention was paid to minimizing drive inertia and to optimizing motor speed reduction in the light of compet-

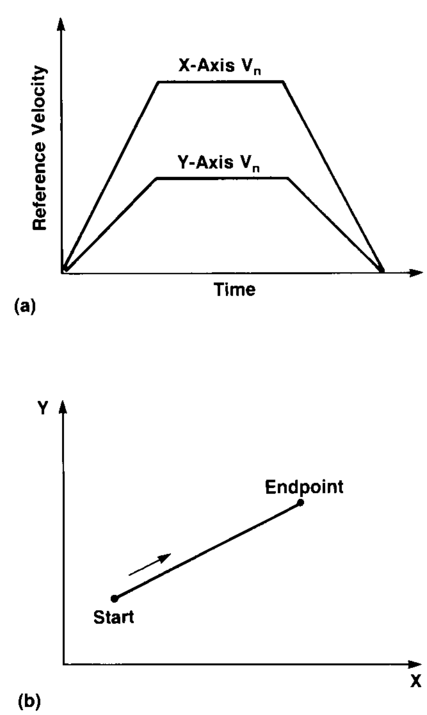


Fig. 3. *(a) Reference velocities versus time for the X and Y axes and (b) the corresponding plot of X versus Y with a slope = ½.*

ing concerns. Increasing the drive ratio improves encoder resolution and improves servo robustness by making motor inertia, which doesn't vary, dominant compared to load inertia, which does. On the other hand, the efficiency of power transfer from motor to load decreases with increased drive ratio, at least in the neighborhood of the HP 7550A's design parameters. In the final design, the load inertia reflected to the motor is approximately 35% of the total inertia and the encoder resolution is 4 counts per P.U. (1 P.U. = 0.025 mm).

Mounted on each motor is a 500-line optical encoder leveraged from another successful plotter line—the HP 7470 family of personal plotters.[1] Also leveraged from the HP 7470 family is the idea of driving the pen carriage with a timing belt. Converting rotary to linear motion via a timing belt has proven to be cheap, easy to assemble, reliable, nearly backlash-free, and—with aramid-fiber reinforced belts—quite rigid. And, of course, the paper moving technology introduced by HP with the HP 7580A[2] is continued in the HP 7550A.

Another key design strategy was to minimize the number of mechanical and electrical parts, maximizing the functionality of each. Thus all servo digital electronics, equivalent to dozens of off-the-shelf ICs, are integrated into a single VLSI package, saving part cost, board space, power consumption, and assembly cost. Similarly, two highly complex injection-molded plastic parts form the mechanical skeleton of the machine, providing not only the structural rigidity necessary to support 6g accelerations, but also the writing surface, the vacuum plenum for paper hold-down, many attachment points for other components, and even an electrical grounding path for protection against static discharge.

We also sought to minimize the number of adjustments made during assembly of the machine. Speed reduction between motor and output drive, for example, is done with spring-tensioned timing belts instead of gears, saving a tricky backlash adjustment. Timing belt drives are also quieter and less expensive. Closing the servo loop in the microprocessor rather than through analog hardware not only eliminates expensive power-hungry components that are not easily integrated into compact circuits, but also eliminates the potentiometer adjustments generally associated with analog servo circuitry.

Probably the most powerful strategy employed to keep cost down and performance up was taking full advantage of the machine's intelligence, the microprocessor. (The 68000 is the brain inside some of today's more advanced personal computers.) For example, the gain of each pulse-width-modulation (PWM) motor drive amplifier is proportional to the voltage supplied to it. Rather than install expensive circuitry to regulate this voltage, we allow it to vary. The microprocessor periodically senses this voltage (via inexpensive PWM-style circuitry) and adjusts input to the drivers accordingly.

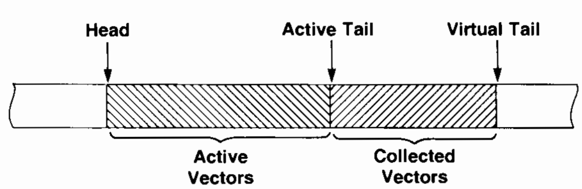


Fig. 4. *The HP 7550A's curved-line generator uses a FIFO buffer to collect data describing vectors before they are plotted. Pointers shown are used to indicate vectors being plotted.*

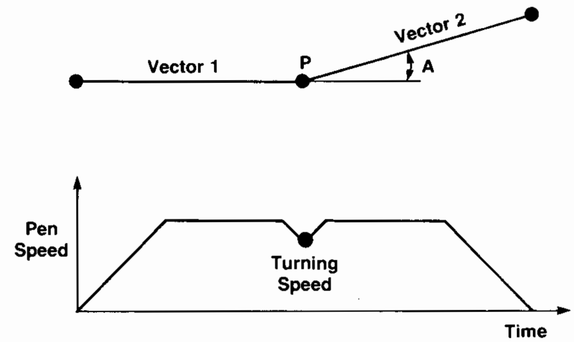


Fig. 5. *The turning speed at the junction of two successive vectors is an inverse function of the turning angle A.*

Another variation for which the microprocessor provides compensation is in the motors themselves. Because of manufacturing tolerances, dc motor gain may vary as much as 25% from nominal. Inasmuch as dynamic matching of the axes is a key to good line quality, mismatched X and Y motors could produce unsatisfactory plots. To head off this potential problem, the plotter's firmware includes a self-calibration procedure, performed in the factory. During a series of programmed moves, the performance of the two servos is analyzed by a special algorithm and the result used to adjust forward-loop gain K_p on each axis. This adjustment is stored in nonvolatile memory.

Because the HP 7550A presses motor performance to its limits, we have observed that some "pathological" plots (generally with certain types of solid area fill) can cause the motors to overheat. Rather than derate the machine for all plots—making all users pay for the needs of a few—we again resort to firmware. During plotting, the microprocessor continuously monitors the power demanded of each motor. Whenever either motor has more demanded of it than can be sustained under worst-case conditions, the nominal acceleration of the plotter is reduced to 3g until that motor has a chance to cool down.

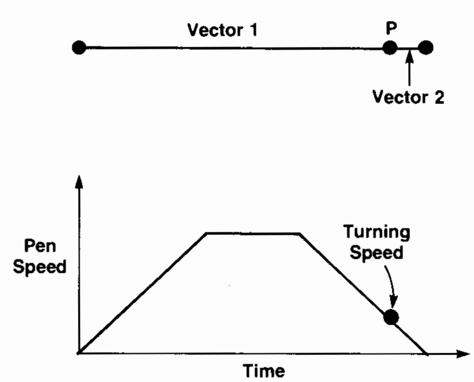


Fig. 6. *The turning speed at the junction of two successive vectors is also a direct function of the length of the second vector.*

Acknowledgments

The successful development of the HP 7550A servo was a team effort. The authors would like to thank Kevin Bockman, David Ellement, Tammy Herr, Peter Ma, Randy Coverstone, and Mark Majette for their numerous contributions.

References

1. A.K. Wilson and D.E. Johnson, "Plotter Drive Motor Encoder Design," *Hewlett-Packard Journal*, Vol. 33, no. 12, December 1982, pp. 26-27.
2. R.J. Kaplan and R.S. Townsend, "X-Axis Micro-Grip Drive and Platen Design," *Hewlett-Packard Journal*, Vol. 32, no. 11, November 1981.

Firmware Provides Simple and Powerful Plotter Operation

by Thomas J. Halpenny

AN ESSENTIAL INGREDIENT in the success of the HP 7550A Graphics Plotter design was shifting as much complexity as possible from the electronic hardware to the microprocessor firmware. A 68000 microprocessor, running at 6 MHz, was chosen to accomplish the objectives. This choice centered on the following:

- The instruction set allows compatibility with the HP-GL firmware of the HP 7580 family of drafting plotters, and provides a growth path for future plotters.
- The processor is fast enough to perform the X-axis and Y-axis servo computations every 300 microseconds, and the pen-axis servo computation every 600 microseconds.
- It has multiple interrupt capability with no additional electronics. The system has a 300-microsecond time base interrupt, a serial I/O interrupt, and an HP-IB I/O interrupt capability.
- The 68000 has a large linear address space to simplify electronics and firmware.

Front Panel

The HP 7550A front-panel controls and indicators are designed to be simpler, friendlier, and more flexible than

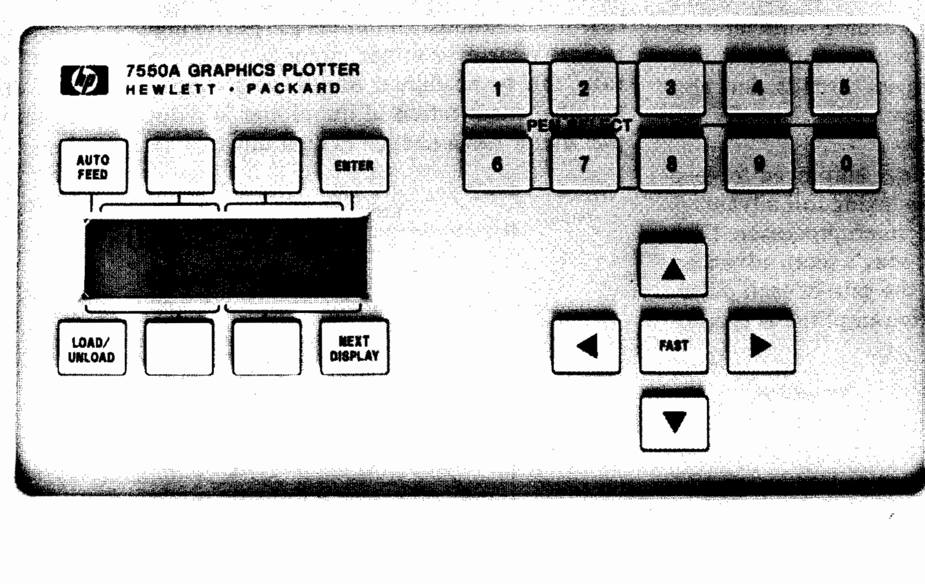


Fig. 1. *Front-panel layout of the HP 7550A Graphics Plotter.*

those of earlier plotters. Early HP plotters had several pushbuttons and LED indicators to perform setup functions and display status. As these plotters evolved, more functions were added to the front panel in the form of more pushbuttons and LEDs. Many users told us that the front panel was getting to be too imposing. Too many pushbuttons and LEDs made it difficult to separate the most often used functions from those that were seldom used. At the same time, the early plotters had a rear panel with an ever-growing bank of configuration switches used primarily to establish the HP-IB or RS-232-C interface configuration with the host computer.

The HP 7550A has a simple layout of three groups of front-panel controls (Fig. 1). The numbered keys are used for manual selection of pens and the number of copies to be plotted. The cursor keys are used to position the pen. The keys that surround a two-line-by-16-alphanumeric-character liquid-crystal display perform all the rest of the functions. The rear-panel switches of previous plotters are entirely replaced by this last group of keys and the display, along with an EAROM (electrically alterable read-only memory) to maintain the configuration in nonvolatile memory. Four of the keys are unlabeled. These softkeys are used with the display and the **NEXT DISPLAY** key to access a menu structure of up to four softkey functions per display.

The result of this layout is a structure in which the most often used functions are the easiest to access, while the seldom used configuration functions are hidden. The paper loading functions have dedicated keys because the user needs these functions often.

The HP 7550A has a dual I/O capability. Either HP-IB or RS-232-C interfaces can be used to communicate with the host computer. The firmware automatically senses which interface is used to communicate with the plotter. This interface is enabled and the other one is shut down. The plotter thus frees the user from having to worry about one more configuration switch. The plotter also automatically senses paper size, a function that required a configuration switch on an earlier plotter.

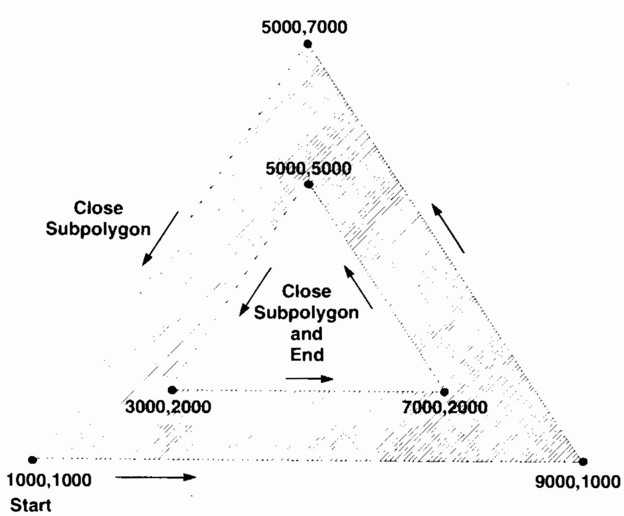


Fig. 2. *Example of polygon generation and area fill as performed by the HP 7550A. See text for associated HP-GL commands.*

The liquid-crystal display also enables the HP 7550A to communicate plotter status to the user much better than before. If the plotter requires operator attention, the display can supply the required message in English. The display is also available to the host computer for display of messages and is used to make internal factory self-tests more versatile than before, at no extra cost.

Firmware Enhancements

Most of the major firmware enhancements of the HP 7550A are centered on the existence of 12,800 bytes of RAM in the plotter. This is called graphics memory and is divided among the following five graphics buffers:

- HP-GL instruction input buffer
- Polygon area fill and edging buffer
- Downloadable character set buffer
- Replot buffer
- Vector buffer.

Each of these subsystems is initially assigned a reasonable amount of memory that will enable it to operate properly under most plotting conditions. The user can change the allocations, however, to increase the memory allocated to a particular buffer, at the expense of other buffers which might not be used at all.

The HP-GL instruction input buffer accepts all graphics instructions from a host computer and holds them until the plotter is ready to execute them. This buffer has been resident in most earlier HP plotters, but until now had always been a fixed size.

The polygon area fill and edging buffer holds polygon vertex and line intersection information to enable the plotter to edge and fill a polygon with a large variety of fill patterns automatically. The vertices of the polygon are sent to the plotter using the same instructions as the computer would use to send vector information to plot. This is accomplished by placing the plotter into polygon mode, sending the vertices, and then returning the plotter to vector mode. At this time the host computer can send instructions to fill and edge the polygon. This scheme allows the host computer to use the same scaling operations for polygons as it does for regular vector information.

The following example illustrates how the host computer can use simple HP-GL instructions to define and fill a polygon. An HP-GL instruction consists of a two-letter mnemonic to specify the operation, followed by a number of parameters, and ending with a semicolon. Table I lists and defines the HP-GL instructions used below.

The following set of HP-GL instructions will generate the simple polygon shown in Fig. 2:

```
PU; PA 1000,1000;
PM 0;
PD; PA 9000,1000, 5000,7000, 1000,1000;
PM 1;
PA 3000,2000, 7000,2000, 5000,5000, 3000,2000;
PM 2;
LT 4; FT 3,50,45; FP; LT; EP;
```

Notice that this figure has a "hole" in it. This is made possible by using the PM 1; instruction to define the polygon as a number of subpolygons. Whenever the user does

Table I

HP-GL Mnemonic	Action
PU;	Pen up (raise the pen)
PD;	Pen down (lower the pen)
PA X,Y;	Plot absolute (move to coordinates X,Y)
LT 4;	Line type (dashed line pattern 4)
LT;	Line type (solid line pattern)
PM 0;	Polygon mode 0 (clears polygon buffer and enters definition mode)
PM 1;	Polygon mode 1 (closes current subpolygon, i.e., allows holes)
PM 2;	Polygon mode 2 (closes current subpolygon and ends definition mode)
FT P,S,A;	Fill type (pattern P, line spacing is S plotter units, and line angle is A degrees)
FP;	Fill polygon interior with fill type
EP;	Edge polygon with line type

this, the currently defined subpolygon is closed, and a final vertex is added to the subpolygon to return to the starting coordinates of the subpolygon definition. The HP-GL instructions for this example include the closing endpoints of each of the two subpolygons, but these were unnecessary.

The DL (downloadable character) instruction allows a user to design characters and save them in the downloadable character set buffer for convenient repeated use in labeling instructions. A character is defined by sending to the plotter its ASCII character code, followed by a sequence of pen-up, pen-down, and X-Y coordinate instructions that one would use to draw the character on the character generator's primitive grid coordinate system. The resulting characters can then be manipulated with the same size, direction, slant, and positioning transformations that can be used with the resident character sets. Up to 94 separate characters can be specified, each associated with a unique ASCII printing character.

The replot buffer is capable of holding an entire plot's worth of HP-GL instructions, depending on the length of the plot. The host computer can then command the HP 7550A to make up to 99 copies of the saved plot without having to retransmit the data. The sheet feeder automatically changes pages between plots. The following HP-GL instruction sequence is used:

BF;	Buffer plot (clear replot buffer and begin storing data)
RP 5;	Replot (make 5 copies of the saved plot)

The BF and RP functions can also be activated using the front panel, in case the user does not have access to the host computer's data stream. This allows a user to capture a plot and make several copies manually.

The HP-GL graphics instructions are stored in a compacted format to maximize data storage capacity. This function is best used in conjunction with other advanced HP-GL instructions. For example, if the host computer uses the plotter's character generator, then only one byte of storage is required for each character drawn. However, if the computer uses PA instructions to draw each stroke of a character individually, then at least four bytes are required for each vector drawn.

The vector buffer is used to hold primitive vector and pen-lift information. It is used by the curved line generator to collect curves, and it helps to increase plotting throughput. This buffer is described in more detail in the servo article on page 31.

Acknowledgments

Dee Setliff did the HP-GL graphics and front-panel firmware. Paul Johnson did the serial and HP-IB I/O firmware. Andrea Frankel provided the character generator extensions for this product and for the HP 7580 Drafting Plotters. Thanks to Lynn Wheelwright for providing us with the 68000 compiler, which was necessary to ensure compatibility with HP 7580 Plotters. Special thanks to Don Harris, whose firmware QA efforts found over half of the bugs discovered.

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