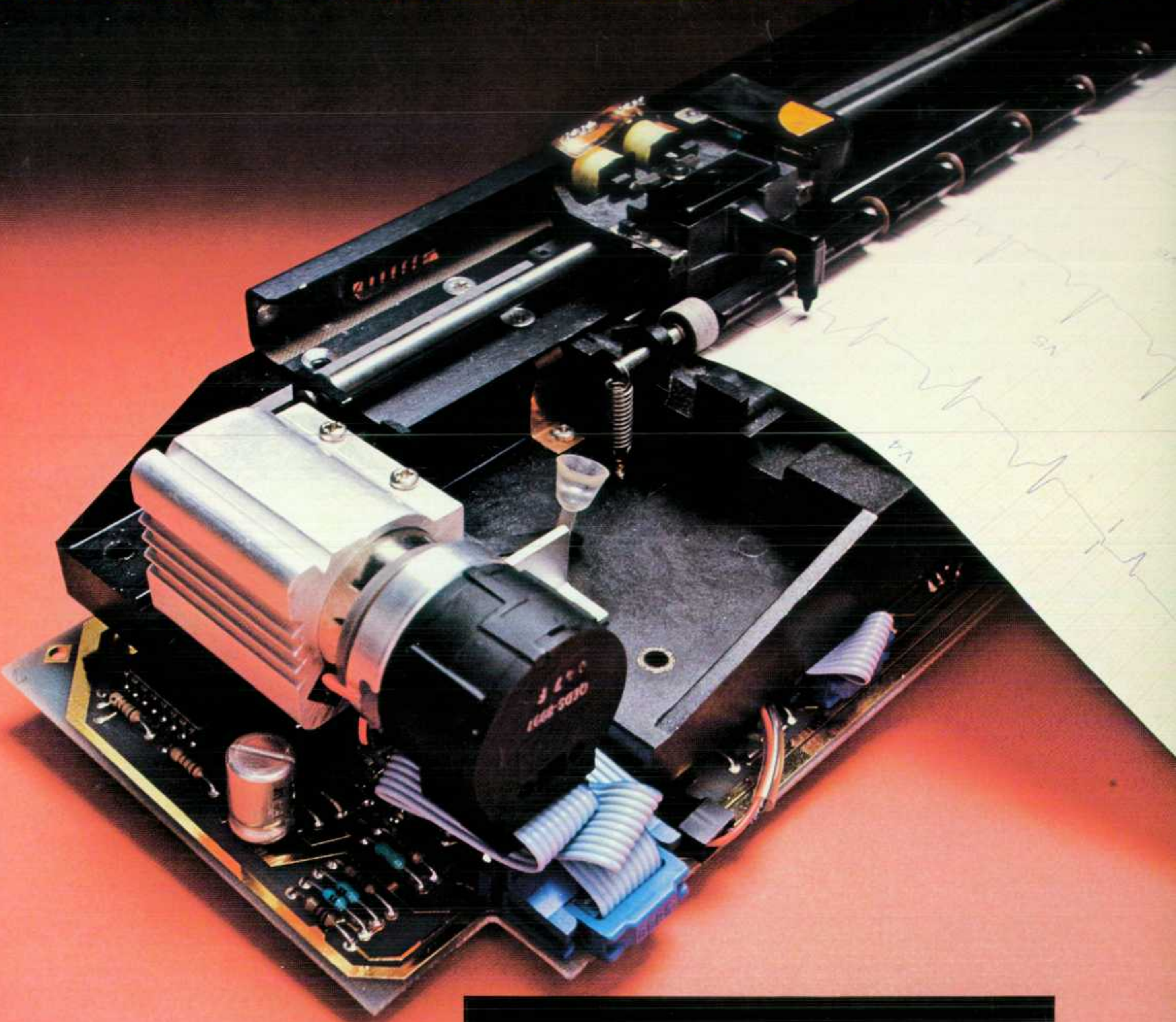
OCTOBER 1981

HEWLETT-PACKARD JOURNAL



HEWLETT-PACKARD JOURNAL
Technical Information from the Laboratories of Hewlett-Packard Company

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This issue and next month's issue are devoted to a new X-Y plotting technology. An X-Y plotter is a machine that draws pictures under the control of a computer. My first look at this new kind of plotter was an eye-opening experience. For one thing, the pen was moving faster than any plotter pen I had ever seen. But the truly astonishing part was that the paper, driven by rollers, was moving back and forth just as rapidly! As I watched, Chuck Tyler, one of the authors of the article on page 3, removed and reinserted the paper several times and repeated the same plot. Yet despite the rapid pen and paper motion and the removal and reinsertion of the paper, it was difficult to tell that each line in the plot had been drawn over several times, so accurate was the plotter.

The article on page 3 traces the evolution of this new plotting technology from its beginnings in HP Laboratories to its ultimate use in a new electrocardiograph (ECG) from HP's Andover, Massachusetts Division and a new large-format plotter from HP's San Diego, California Division. Described on pages 8 and 10 are two special components that were developed to make it practical to use the new technology. One is an integrated-circuit chip that contains most of the necessary control circuits and the other is an optical encoder used for sensing the motion of the motors that drive the plotters. The encoder is available as a separate product, Model HEDS-5000. Its advantages are small size, high resolution, reliability, and ease of assembly.

The new electrocardiograph, Model 4700A PageWriter Cardiograph, is the subject of the article on page 16. Its most obvious difference from conventional cardiographs is that it uses standard sheets of paper instead of a narrow roll. The records it produces are accurate, clear, concise, automatically labeled, and easier to read, handle, interpret, and file than conventional cardiograms. On a single sheet of paper it can put all of the standard 12-lead ECG information plus the rhythm trace that shows heartbeat regularity. It can remember an ECG record and rerecord it on command, and it can save and later expand selected portions of an extended rhythm record for closer examination by the cardiologist. Its memory feature is useful for making multiple copies of an ECG record.

Our cover this month shows a portion of the recording mechanism of the 4700A Cardiograph. You can see the HEDS-5000 Optical Encoder—the black cylinder—mounted on the end of the pen-drive motor. The inset photo shows the assembled cardiograph. Next month's issue will be devoted to the large-format plotter, Model 7580A.

-R. P. Dolan

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Development of a High-Performance, Low-Mass, Low-Inertia Plotting Technology

A new vector plotter technology makes possible small, inexpensive graphics products that provide high-quality plots quickly.

by Wayne D. Baron, Lawrence LaBarre, Charles E. Tyler, and Robert G. Younge

THIS AND ACCOMPANYING ARTICLES in this and next month's issues will trace the evolution of a new plotting technology from muse to market. This article describes the authors' early thinking and experimentation in Hewlett-Packard's corporate research laboratories. We will also describe our interaction with colleagues in other parts of the company, and how this focused our work, helping us produce the tools they needed to carry out their product development programs.

Our interest was captured by the success of the pocket calculator. Large scale integration (LSI) of electronic circuits had taken the calculator from the desktop to the pocket. Could a similar reduction in size and cost be achieved for a calculator peripheral? A calculator is an electronic device, a peripheral is an electromechanical device. Could digital control techniques be used to put mechanical cost and complexity into LSI as well? These ideas could be debated endlessly. We decided to test them by casting a tangible objective: a vector plotter for the (other) pocket.

Initial Concept

How do you plot over the surface of a piece of notebook paper with a device that will fit into your shirt pocket? Our solution (Fig. 1) had the plotter grasp the paper along an edge and move it up and down. A steel tape, similar to a common measuring tape, moved a pen back and forth across the paper, so that (almost) any point on the paper could be marked.

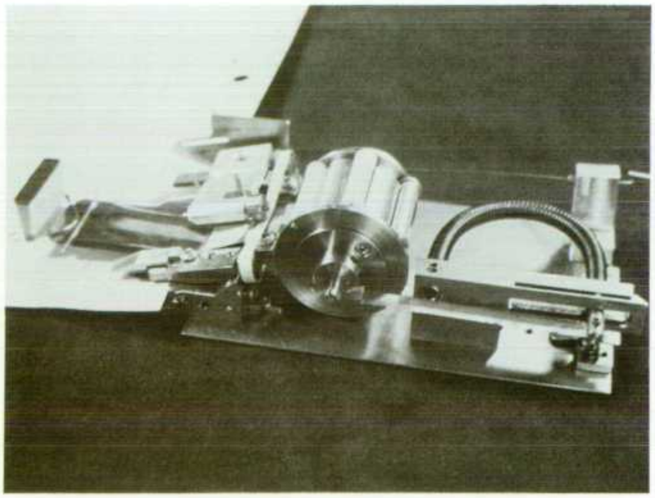

Fig. 1. *This initial mechanism moved the paper up and down by its edge and moved the pen left and right by extending and retracting the steel tape on which it was mounted. A piezoelectric element was used to raise and lower the pen.*

Two rubber rollers pressed the margins of the paper against two drive rollers coated with grit. A guide bar kept the paper edge straight and a minute amount of reversible tilt in the rubber rollers insured that the paper edge remained pressed against the guide bar. The reversible tilt is obtained by containing the outside ends of the roller shafts in holes that are slightly elongated in the two directions of paper travel. During the first pass of the paper through the rollers, the grit rollers (pinions) impressed a minute pattern (rack) on the back of the paper along the margin. Subsequent passes then followed this same pattern, so that paper registration to high precision was realized. The steel tape was driven with high precision by convolute pin gears such as those used in motion-picture film drives.

At this point, our prototype moved the paper in and out and the tape back and forth with hand cranks fashioned from bent wire. How could we replace these with motor drives having adequate speed and control but little more cost? This implied a very simple, all digital control system, without any position encoders, tachometers, or accelerometers. One solution is the step motor, but its power supply and drive electronics are expensive. A dc motor can have a simple drive system, but an encoder to measure shaft angle is necessary for its control. This led us to explore whether a digital shaft encoder could be made for less cost than a step motor drive. Early experiments were encouraging, except for the resolution required to reduce quantization error and thereby eliminate grinding noises at low speeds. Attempts to purchase a satisfactory encoder for less than $150 (US) failed, and this was already much more than we were willing to spend. Fortunately, HP's Optoelectronics Division became interested in this situation, and they were able to build encoders with satisfactory specifications and much lower cost by using their light sensing and emitting, integrated circuit, and precision optics expertise. These devices are described in the article on page 10.

If position encoders are located out on the pen as in earlier slidewire plotters, all system compliance enters as a resonance in the servo system. Putting an encoder directly on the drive motor shaft eliminated this resonance and any deadband caused by the drive linkage. This simplified modeling and understanding. We proposed to keep the outboard mechanisms light, tight and simple so that any compliance there would not degrade graphic quality. Moving only the separate masses of a sheet of paper and a pen made this a practical approach. This is equivalent to making the motor rotor the dominant inertia, which in turn allows identical servo controllers for both axes.

We needed a pen lift at the end of the tape, but weight and battery power argued against a solenoid. We reduced the energy requirement manyfold by rotating the pen about its center of mass, and using a piezoelectric bimorph to drive it.

Our first graphic record (Fig. 2) improved nicely with effort and the mechanism did indeed fit inside an attractive, calculator-sized enclosure (Fig. 3).

First Product Application

As the initial design approached completion, we had the good fortune to be contacted by HP's Andover Division. They wanted to replace galvanometers, which consist of precision parts and skilled labor (both already expensive and increasing rapidly) with some form of inexpensive graphics. Their overall objective was an annotating all-digital electrocardiograph with superior graphic fidelity and quality. We quickly agreed that the initial design was not satisfactory in a hospital environment, and Steve Koerper at Andover made certain we understood how severe that environment could be: if a mechanism could be knocked off its cart repeatedly, stepped on, have serum poured into its works, and still work after months of such abuse, it would be a serious candidate for their attention. Very high pen and paper accelerations would be helpful to reduce the time necessary to produce a record so the cardiologist would know quickly if a faulty electrode connection existed. Again, high graphic fidelity is essential to proper medical interpretation.

To retain the advantages of the initial low-mass, low-inertia design in this new application, we still wanted to move only the paper and the pen. We decided to close the pen drive tape on itself to form a belt and to pass the paper through the belt, again with rollers. This allowed placing the mechanism entirely within a compact, protective structure. The pen could be attached to a precision guide. Grit wheel and rubber roller pairs pinched the paper on opposite edges, causing the resultant force to pass through the center of mass of the paper. This prevented paper buckling by high accelerations. Each track of impressions in the back of the paper was now made by only one grit wheel, enhancing the rack and pinion effect to prevent slippage under the anticipated higher acceleration.

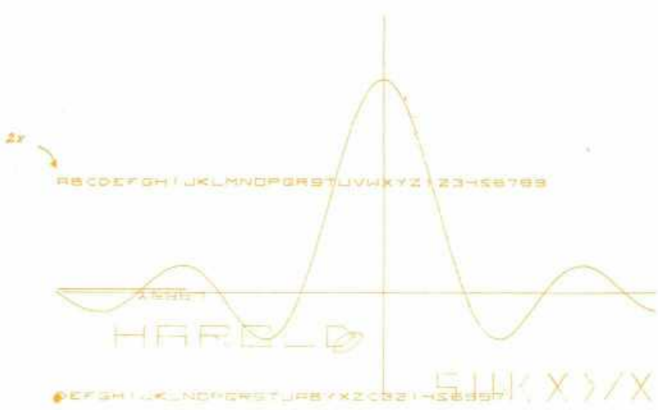

Fig. 2. *First graphic record produced by the mechanism shown in Fig. 1.*

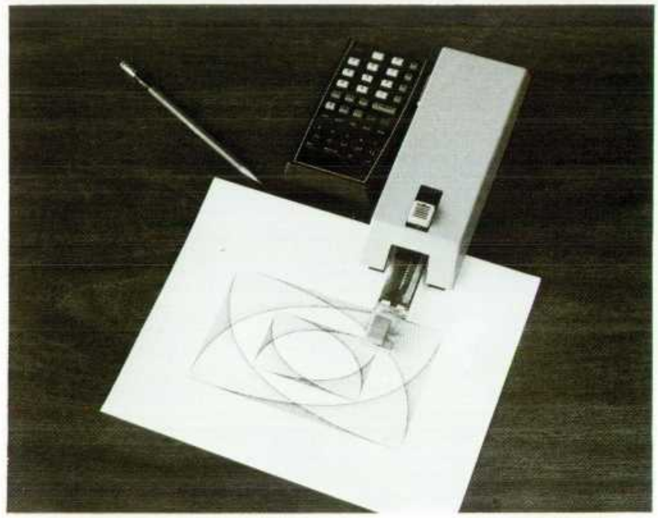

Fig. 3. *Additional effort and refinement of the initial design led to an attractive package capable of producing a quality plot as shown above.*

The control electronics were receiving a similar measure of attention in preparing for higher speed, acceleration, and quality. Some higher-order feedback would be necessary, but adding transducers would compromise our spartan digital approach that promised such attractive low cost. We decided to convert the shaft-encoder period into its inverse and use it as a velocity feedback signal. This required no additional transducers but still provided the feedback we needed for higher performance.

Mechanics and electronics were designed, built, and hooked together. We turned on the switch only to throw the pen out of its holder and three metres off the bench! After

Fig. 4. *Basic mechanism using grit-wheel drive on opposite edges of the paper and a pen driven along a precision guide by a belt loop. Refinements of this basic design are used in the 4700A PageWriter Cardiograph and the 7580A Drafting Plotter.*

Digital Control Simplifies X-Y Plotter Electronics

The dominant theme of the new low-mass, low-inertia X-Y plotter technology is simplicity. This concept is not only prevalent in the mechanism, but is the basis of the electronic architecture (Fig. 1). The job of the electronics is to accept a series of vector and pen lift commands from an external source such as a calculator, computer, or another microprocessor, and then to convert these commands into the appropriate movements of the pen and paper.

The first stage of this process takes place in a custom Z80-based microcomputer. The data received with the commands is converted from user coordinates to the coordinates of the mechanism. From this data the microprocessor determines a velocity profile for the drive motor of each axis that will do the task in minimal time while keeping the line being drawn straight. The output of the microprocessor is a pulse train to each of the servo controllers. Each pulse causes the motor to move a prescribed amount. By commanding the servo with the longest move to perform at its maximum speed and acceleration and synchronizing the movement of the other axis at a slower velocity to it, a straight line is achieved (Fig. 2). This is accomplished by controlling the longer axis with a table-driven velocity profiling scheme and then using the algorithm outlined in Fig. 3 for synchronization. Making the algorithms interrupt-driven assures that the processor does not limit the ultimate speed of the plotter.

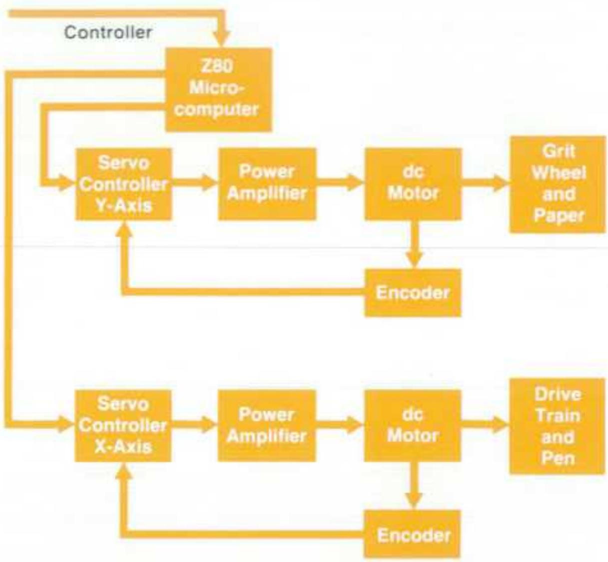

Fig. 1. *Block diagram of low-mass, low-inertia plotter electronics. Note that each axis is controlled by a separate, but identical servo control loop. Coordination between the two axes is handled by the microcomputer upon instructions from a controller.*

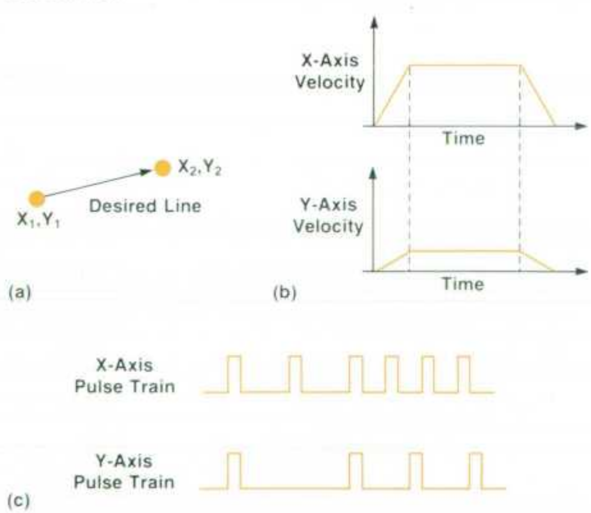

Fig. 2. *To draw a line (a) from one point to another, the axis drive motor requiring the greatest position change is set to its maximum velocity (b) and the velocity of the other axis drive motor is set proportionately. Thus, the drive pulses for each motor (c) will occur at different rates according to the velocities required to draw a straight line.*

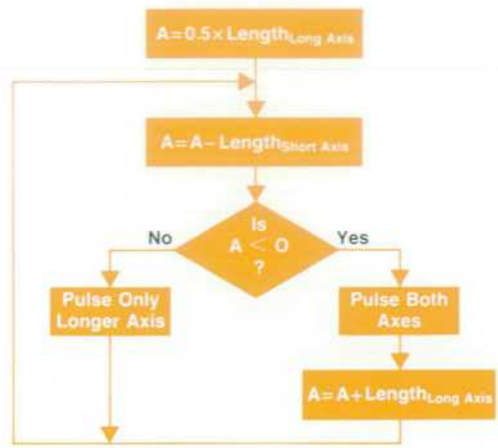

Fig. 3. *Algorithm for controlling pulse rates to each axis drive motor during a move from one point to another.*

The next major block in the architecture is the servo controller. The controller is completely digital to facilitate integration (see box on page 8). The controller's job is greatly simplified by the mechanical structure of the plotter. Since the paper is moved independently along one axis and the pen is moved along the other axis, the two axes are decoupled. Because the position encoders are mounted directly to the back of the drive motors, the problems of resonance are drastically reduced. The dominant inertia of the system is designed to be in the motors. This allows the response of both servos to be matched, which in turn helps keep the lines straight.

The servo controller works much the same as a classical analog servo would. It takes the pulse string from the microprocessor and

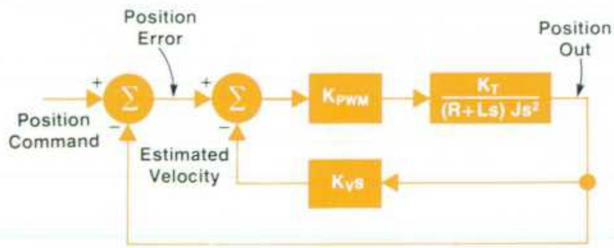

Fig. 4. *Digital servo loop.* K_{PWM} *is the gain of the pulse-width modulator,* K_V *is the velocity feedback gain,* K_T *is the motor's torque constant, and J is the inertia of the mechanism.*

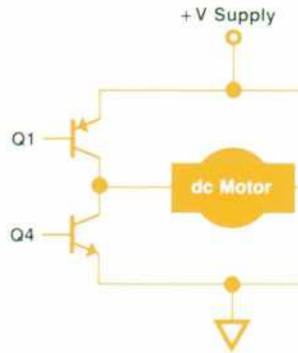

Fig. 5. *Arrangement of power amplifier transistors driving motor for each axis. Appropriate switching of Q1, Q2, Q3, and Q4 allows motor rotation in either direction.*

converts it to an instantaneous position command. At the same time it decodes the quadrature signal from the encoders and determines the current motor position. The difference between these two values is the position error.

For the loop to be stable, it must have compensation (see Fig. 4). In an analog loop this would come from a tachometer. Here a velocity estimate is generated from the encoder signal by using a variation of the reciprocal time method. Thus the need for a second encoder for each axis is eliminated. The velocity estimate is subtracted from the position error to derive the motor command. The motor command is then transformed into a pulse-width modulated signal suitable for driving an H-bridge power amplifier.

The amplifier for each drive motor, in keeping with the all digital theme of the electronics, consists of four transistors which are either turned on or off. By pulsing either Q1 and Q3 or Q2 and Q4, the direction of drive current to the motor can be determined. The average magnitude of the current is controlled by the duty cycle of the pulse.

These currents drive the motors, which in turn move the paper and pen through grit wheels and drive trains respectively, ultimately creating the desired line on the page.

-W.D. Baron

the design of a pen, holder, and guide rod adequate to withstand the new acceleration, we realized an acceleration of 2500 cm/s^2 with good graphic quality, quite beyond anything we had read about or heard of. Fig. 4 shows the new mechanism.

Refinement: Project Sweetheart

This technology needed a name. It was a genuinely satisfying thing to exercise, and it had been wrought for the Andover Division's cardiology team. The name could not be denied: Sweetheart.

We entered a refinement period of repeatedly increasing speed and acceleration until graphic quality suffered, then improving the mechanics, control electronics and software until the quality was regained. Increasingly quick methods for determining the velocity were found, as were better methods of using it to stabilize the servo loop.

New and efficient trajectory control algorithms (see box, page 5) were discovered that allowed high speed and yet could be implemented on a simple Z80 microprocessor. This allowed us to provide greater performance with no increase in electronics cost other than larger motor-driver transistors.

Pen wear became a problem. Higher velocities simply dragged the pen over more paper per unit time, and the much higher accelerations meant many more pen lifts and drops per unit time. These lifts and drops not only hammered the nylon pen tips, but the time they required became an increasingly large fraction of the time to complete a plot containing alphanumeric characters. We needed a much faster, yet gentler, pen-lift technique.

A speaker-coil linear motor was designed with feedback provided by a vane interrupting a light-emitting-diode (LED) optocoupler. This allowed a critically damped design that could drop the pen in less than two milliseconds, yet reach the platen at zero velocity. The system also sampled the platen continuously, allowing manufacturing misalignment of platen and pen guide and freedom from adjustment. A dual-level lift with the initial lift to 0.5 mm followed after 30 ms by a second lift to 2.5 mm meant the pen never lifted above 0.5 mm when printing a line of alphanumerics. This reduced the time devoted to pen lifts even more.

The Sweetheart project had met all its initial objectives. We made numerous prototypes to discover failure modes under various conditions, and they all had an inherent toughness that forgave abuse. Some of these have run for years now with an acceleration of 9400 cm/s^2, speed of 150 cm/s, and 20 characters/s while retaining satisfactory graphic quality.

Andover, having helped us design the missing piece they needed, began to concentrate exclusively on building their digital electrocardiograph. Marco Riera converted the algorithms to a 6801 microprocessor. Marty Mason redesigned the entire mechanism for use as an electrocardiograph component, and added an elegant automatic paper-alignment feature. Marty and Larry Perletz designed a new pen suitable for production. These and all the other contributions that made the HP Model 4700A PageWriter Cardiograph possible are described in the article on page 16.

Could we extend this technology to larger pieces of paper? The condition that the dominant inertia be the motor rotor was still satisfied for much larger paper and pen drive masses. We cut a mechanism in half, lengthened the center until the rollers were just under 56 cm apart, and generated a D-size (56 by 86 cm) plot seven days after beginning the project (Fig. 5).

Marv Patterson of the San Diego Division brought his extensive experience in large-format graphics (and the most insidious diagnostic test routine we had ever seen) to an evaluation of the stretched prototype. He concluded it had real potential for large graphics, and work in San Diego, until then limited to helping us with pens and inks and general technical consultation, began in earnest.

The initial successes with large-format plotting proved deceptive. Plotting on polyester sheets, necessary for many activities such as legally recording subdivision plots in the building industry or master parts files in manufacturing,

Fig. 5. *Engineering team and first large-scale plot made by an expanded version of the basic grit-wheel drive mechanism.*

could not be sustained over long periods without the polyester sheets beginning to slip during a plot. The study, understanding, and correction of this difficulty was led by George Lynch at San Diego and forms a part of a set of articles on large-format plotting in next month's issue.

To design integrable digital control circuitry is one thing, to produce a satisfactory integrated circuit is another. Clement Lo of the Corvallis Division asked numerous questions about our circuit until he understood its operation in the electromechanical control environment. He executed a radical redesign that was essentially the same functionally, but was much more reliable and took maximum advantage of the process he had selected. He and his team then brought in the first working silicon chip ahead of schedule. The box describes this work in more detail.

The promise of combining LSI and digital control has been largely verified, and its commercial realization is just beginning. The new technology provides higher graphic quality and much higher accelerations, yet much lower cost and power consumption than previous art. It can serve a broad range of applications, from a small component within an instrument to a large, stand-alone plotter. Articles in this and next month's issue describe the first products.

These programs have been characterized by conceptual and strategic partnerships of Hewlett-Packard's research laboratories and operating divisions early in the programs, sharing of concerns and suggestions throughout, and the operating divisions discovering and solving some of the more subtle and more difficult problems at the end.

Charles E. Tyler

Chuck Tyler earned the BS degree in physics in 1964 at the Massachusetts Institute of Technology. He then received the MS and PhD degrees in physics from Washington University, St. Louis, Missouri, in 1969. Chuck joined Hewlett-Packard Laboratories as a staff member and now is director of the Applied Physics Lab. He is the author of several papers and an inventor on several patents. A native of Sabinal, Texas, Chuck is married, has two children, and lives in Sunnyvale, California. His interests include ranching, hunting, and fishing.

Lawrence LaBarre

Larry LaBarre joined HP in 1952 with ten years of experience in designing fishing and concrete ships, sawmills, and sawmill machinery. At HP he has designed the 608, 626, and 628 Signal Generators, waveguide and waveguide tooling, and the automatic injection and high pressure pump portions of gas chromatographs. Larry directed special machine work for several years and is now working on low-mass, low-inertia plotter mechanisms. Larry is an inventor on several patents related to an automatic typewriter punch, lapping machinery, automatic injection for gas chromatography, and the grit-wheel paper-drive plotters. He was born in St. Paul, Minnesota and for a time attended the U.S. Naval Academy by presidential appointment. Larry then studied aircraft engineering and shipbuilding through the International Correspondence Schools. He lives in Mountain View, California and is interested in occult philosophy, health, and mechanisms.

Robert G. Younge

Rob Younge joined HP in 1975 after receiving the BSEE (1974) and MSEE (1975) degrees from Stanford University. He was a department manager in Hewlett-Packard Laboratories before he left the company to become one of the founders of Acuson. Rob is the co-inventor of one patent (pending) and a member of the IEEE. A native of Grand Junction, Colorado, he now lives in Menlo Park, California and enjoys backpacking and music.

Wayne D. Baron

Wayne Baron was born in Philadelphia, Pennsylvania and attended the Massachusetts Institute of Technology where he received the BSEE and MSEE/Computer Science degrees in 1977. Wayne started at HP as a co-op student in 1974, working on frequency synthesizers. He began full-time work in 1977 as a staff member in Hewlett-Packard Laboratories and now is a project manager. Wayne lives in Cupertino, California and enjoys skiing, folk dancing, and camping.

Plotter Servo Electronics Contained on a Single IC

by Clement C. Lo

The new X-Y plotter technology described in the accompanying article allows the designer to reduce the complexity and cost associated with the servo control electronics of an electromechanical device. Hewlett-Packard Laboratories built numerous prototypes that established the relationship between the digital control circuitry and the mechanism. To achieve the objectives of low cost, small size, low power consumption and high reliability, all of the required digital servo control electronics except the high-current motor drivers were integrated into one NMOS integrated circuit.

The basic plotter servo system for one axis (Fig. 1) consists of a host processor, the servo controller IC, motor drivers, and a dc motor with a quadrature encoder mounted on the shaft. The servo logic can be divided into five major sections:

1. Arithmetic logic unit (ALU) to perform the summing and error-keeping functions (Fig. 2a).
2. Read-only memory (ROM) which stores the predetermined velocity profile of a given electromechanical system.
3. Decoding logic to decode information sent by the host processor or the quadrature encoder signals.
4. Velocity estimation logic.

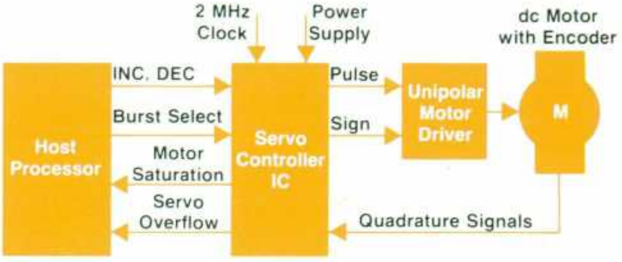

Fig. 1. *Block diagram of servo control system for one axis of a low-mass, low-inertia plotter. One IC contains all of the digital servo control electronics, greatly simplifying the overall system design.*

5. Pulse-width modulation logic.

The architecture of the NMOS servo controller (Fig. 2b) is in many ways a refinement of the initial servo designs. However, the total integration of the whole servo control system into one low-

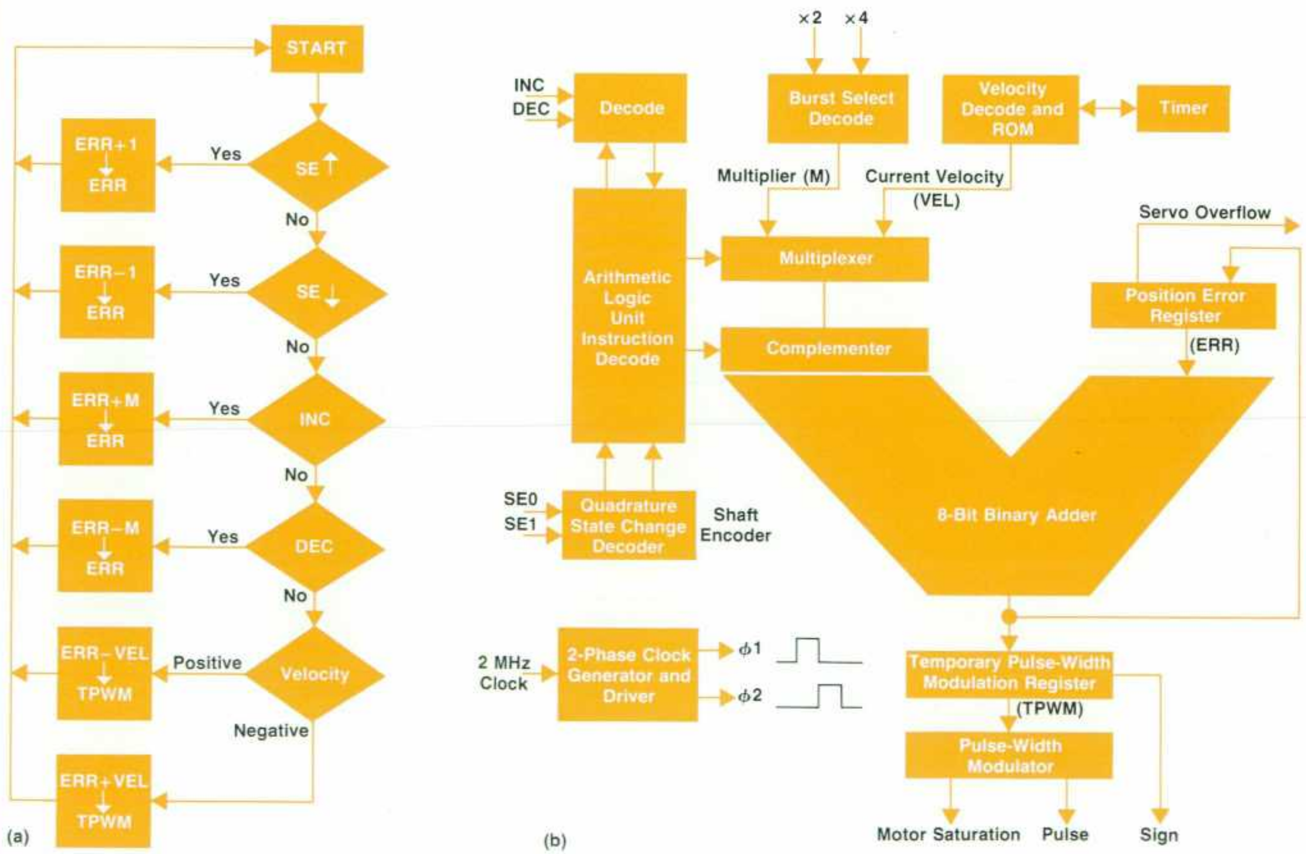

Fig. 2. *(a) Instruction flowchart for ALU used in servo controller IC. (b) Architecture of digital servo control system. This system is fabricated on a single NMOS IC.*

power integrated circuit called for new techniques in both logic and circuit design.

Positioning commands are in the form of INCrement or DECrement. The host processor commands the servo controller with INC, DEC and the burst select inputs (×2, ×4). The direction of motor rotation is determined by either INC or DEC. The number of steps the motor will rotate upon each INC or DEC command is determined by the logic states of the burst select inputs. They provide a multiplication factor of 1, 2, 4, or 8. The servo controller implements the position error summing, velocity feedback summing and error amplification function by using an eight-bit ALU. The velocity decoder obtains the velocity by measuring the time between the shaft encoder quadrature state changes and comparing it to a velocity lookup table stored in an on-chip ROM. The amount of ROM space required for the entire dynamic range is reduced from 512 bytes to 64 bytes through a novel autorange technique.

The servo controller sends two warning signals back to the host processor. Under normal operation both the motor saturation and servo overflow outputs should be at a logic zero state. When the output of the pulse-width modulation logic reaches a 90% duty cycle, the motor saturation output will go to a logic one state. Once it reaches a 100% duty cycle, the servo cannot accelerate the motor any faster and will fall behind. This will eventually cause the controller to lose the shaft position. The position error register can hold ±127 steps. When an overflow situation occurs, the servo overflow output will go to a logic one state and the controller will automatically shut off the drive signals to the motor. The controller will remain in this state until reset by the host processor.

Fig. 3 shows a picture of the integrated circuit. This 3.48-mm-by-3.3-mm IC dissipates about 100 mW at a clock frequency of 2 MHz. Numerous logic cells are used and most of the random logic is implemented by programmable logic arrays (PLA). This greatly reduces the complexity of the layout and was one of the prime factors in the speedy turnaround of the design. The timing of the logic also maximizes the speed/power tradeoff to achieve low power dissipation.

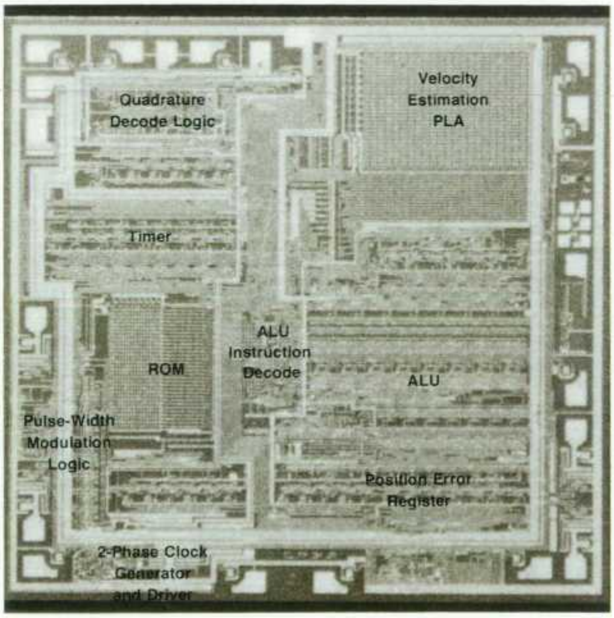

Fig. 3. *Microphotograph of servo controller IC with various functional areas identified. This chip is 3.48 mm wide and 3.3 mm high, roughly this size:*

Acknowledgments

I would like to thank Mike Pan for the excellent job he did in circuit design and detail checking of the chip. Don Hale did the layout. Jerry Erickson did the logic simulation of the circuit and Dave Serisky implemented the CMOS breadboard. Special thanks to Mike Lee of HP Laboratories for his advice and encouragement.

Clement C. Lo

Clement Lo was born in Hong Kong and attended the University of California at Berkeley where he was awarded the BSEE degree in 1974. Clement then earned the MSEE degree in 1975 from the University of California at Los Angeles (UCLA). He came to HP in 1975 and has worked on several ICs for the HP-85 Computer and was project leader for the servo-controller chip used in the 4700A. Clement is a project manager in the R&D lab at HP's Corvallis Division and is a co-author of an article on a printer-controller chip. He is married and lives in Corvallis, Oregon. He enjoys woodworking, gardening, and using small computers.

An Incremental Optical Shaft Encoder Kit with Integrated Optoelectronics

This kit can be assembled easily by an OEM (original equipment manufacturer) to provide accurate digital information about shaft position and velocity in digitally controlled electromechanical systems.

by Howard C. Epstein, Mark G. Leonard, and John J. Uebbing

THERE IS AN INCREASING DEMAND for digital control of mechanical motion. Incremental shaft encoders allow closed-loop control by sensing the rotational position of the system. A controller compares the actual and desired shaft positions and generates motor drive signals to reduce the difference. Velocity information for damping the servo loop is also obtained from the encoder signals. This combination of a motor and an encoder in a closed-loop system gives improved acceleration, optimized damping, and low power consumption.

The HP HEDS-5000 Encoder Kit (Fig. 1) is an incremental optical shaft encoder kit designed especially for use with small electric motors in applications such as printers, plotters, disc and tape drives and machine controls. It features small size (28-mm diameter), low power consumption, operation from a single 5-volt supply, and high reliability. Even though it can have as many as 500 pulses per revolution, it has a low sensitivity to radial and axial play in the shaft. This allows it to be used with lower-cost motors.

Central to the product's contributions are integrated optoelectronic components that are designed specifically for use in incremental shaft encoders. This was done by extending the design and manufacturing techniques developed at HP's Optoelectronics Division in light-emitting-diode (LED) materials, in photodetector integrated circuit design, and in precision plastic lens molding.

Fig. 1. *The HP HEDS-5000 encoder Kit makes it easy to add the capability of sensing shaft position and velocity for digital control. The kit has three parts: an encoder body containing the phase plate and detector module, a code wheel assembly, and an endplate containing the emitter module.*

Design Objectives

The encoder design evolved in an interactive process with several HP divisions that were developing precision electromechanical motion systems. They wanted a combination of encoder features that were then unavailable commercially.

Some of the applications were in portable equipment, so the encoder had to be small and compatible with battery power (low power consumption, single unregulated supply). Motors can be bought with precision bearings, but if the encoder can tolerate some end play and wobble, reliability is increased and motor cost can be reduced. Some applications needed a once-per-revolution index pulse in addition to position and direction information. Others wanted an analog signal for interpolation between digital pulses. There also was the list of qualities wanted in any product: low cost, high resolution, ease of assembly, long life, and wide operating temperature range.

A study of the basic geometry of encoders and their signal errors indicated that three factors are very important: collimation, the distance between channels, and sensitivity to light level changes. Collimation determines the resolution available in an encoder. Spacing between channels controls sensitivity to shaft wobble and centering errors. Light level changes can affect signal duty cycle.

A strategy was developed to build a set of emitter/detector modules that would have improvements in the three critical areas. The requirement for well collimated light is satisfied by an LED with a small emitting area and a precision-molded collimating lens. The second and third requirements, close spacing between channels and insensitivity to brightness changes, are satisfied by a differential (push-pull) detector IC containing two detectors, dual amplifiers and a comparator.

The resulting modules are designed to work with a large range of count densities and encoder sizes. The small 28-mm 500-count HEDS-5000 Encoder Kit is the first of a family of products that will use them. The low sensitivity to axial and radial shaft play makes the kit easy to assemble on

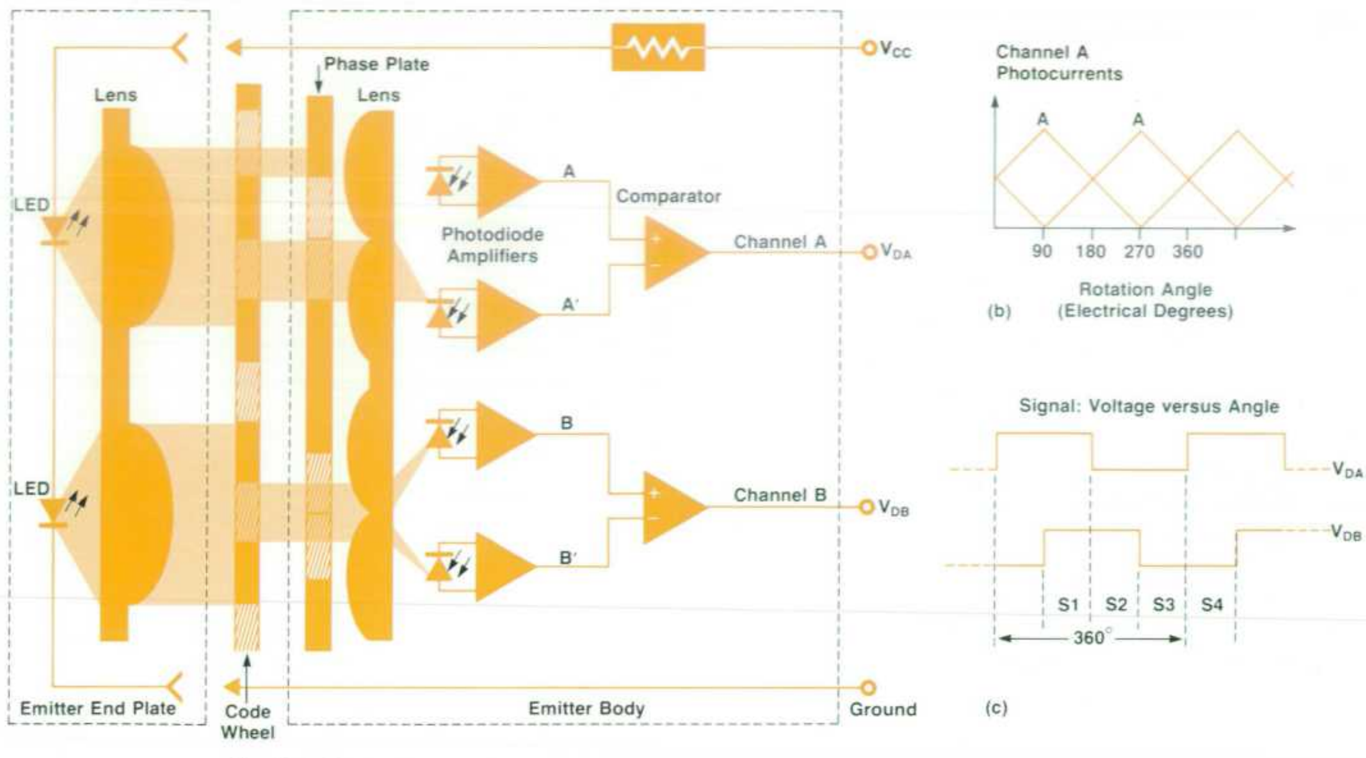

Fig. 2. *(a) Block diagram of transmissive optical encoder. Light is emitted by LEDs and focused into beams that impinge on the code wheel. The light passing through the openings in the code wheel pattern is incident on the phase plate. The two detector channels then detect the amount of light that passes through the openings in the phase plate. (b) Photocurrent waveforms for pair of photodiodes in one channel. These photocurrents are amplified and compared to generate a digital output waveform for each channel as shown in (c).*

the customer's shaft. The kit approach is less expensive than providing encoders with their own shafts and bearings and results in stiffer mechanical coupling.

HEDS-5000

The HEDS-5000 senses shaft motion by interrupting a collimated light beam with the spokes of a code wheel and detecting the rotating pattern of shadows. A block diagram is shown in Fig. 2a. The output signals are two similar digital waveforms. Each cycle (360 electrical degrees) corresponds to the angle between code wheel spokes. The photocurrent waveforms for the photodiode pair in one channel are shown in Fig. 2b. They are processed by the amplifiers and comparators for each channel to form the two digital outputs shown in Fig. 2c.

The digital waveforms are in quadrature, that is, separated in phase by 90 degrees. Together they form four logic states, labeled in Fig. 2c as S1, S2, S3, and S4. For positive rotation they occur in the sequence S1, S2, S3, S4; for negative rotation they occur in the order S1, S4, S3, S2. Besides indicating direction, the four states can be used for intracycle position information.

The encoder (Fig. 1) has three parts: the emitter end plate which provides the collimated light source, the code wheel, and the body which contains the detectors. The assembly sequence is indicated in Fig. 3. The cup-like body is first screwed to the mounting surface. The code wheel is then fixed to the shaft with epoxy adhesive and the emitter end plate is snapped into the body to form a dust-resistant assembly.

Principles of Operation

The basic geometry of one channel of a transmissive encoder is illustrated in Fig. 2a. Shadows from the rotating code wheel fall on a stationary mask (phase plate) that covers the detectors (photodiodes). Openings in the phase plate are the same size and shape as those in the code wheel (equal transparent and opaque segments). Together they form shutters through which light transmission is a linear function of angle. This produces photocurrents that have a triangular waveshape.

Each channel has two detectors and the openings in the phase mask are positioned to produce two signal currents that are 180 degrees out of phase. A digital output is produced by comparing the two signals. A logic high occurs when the first detector A receives more light than the second detector A'. Both detectors in each channel are illuminated by the same LED. This differential detection approach has the advantage of making the digital signal insensitive to variations in light source brightness. Differential detection does depend, however, on equal illumination of both sides of the channel and matched detector responses. The sensitivity to imbalance is a 0.9° change in the total pulse width (nominally 180°) for each 1% mismatch in illumination or detector response.

Error Sources

The usual matching procedure for differential encoders is

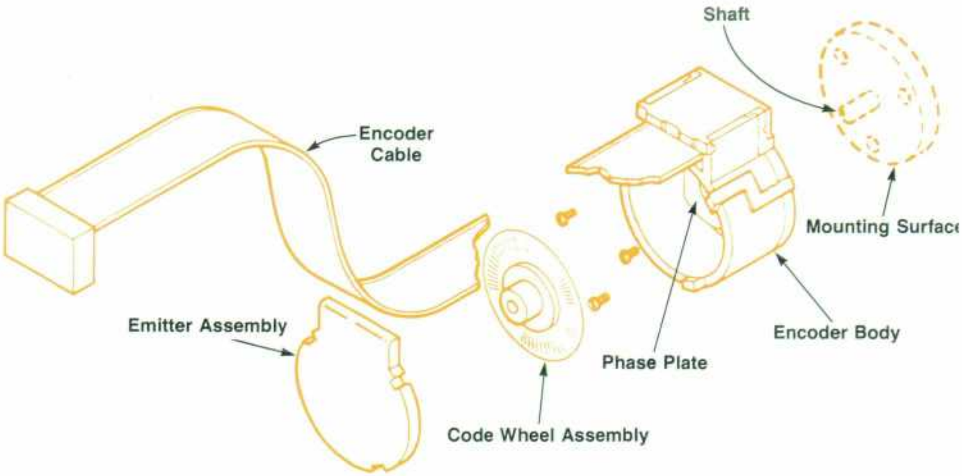

Fig. 3. *Assembly sequence. The encoder body is mounted to the housing containing the shaft (typically a motor body). The code wheel is slipped on the shaft and secured with epoxy adhesive. The emitter endplate then snaps into place to complete the assembly.*

to adjust the gain of detector amplifiers individually to achieve balance. The HEDS-5000 has matched detectors and a low-offset comparator that are obtained by fabricating them on the same IC. The emitter lens is designed to provide uniform light intensity across the face of the light beam. The result is balanced detection that does not require adjustment and contributes to high reliability and low cost.

Resolution depends on the degree of collimation of the light source, the spoke-to-spoke distance, and the separation (gap) between the code wheel and the phase plate. These factors determine the sharpness of the code wheel's shadow. As the edges of the shadows become blurred, the peaks of the triangular output waveform become rounded. The collimation of the HEDS-5000 emitter allows the encoder to operate effectively at gaps up to 7 times the cycle distance. This represents about a fivefold improvement over light sources used on most encoders. The high gap tolerance (1 mm) is used to provide large reliability guardbands against the code wheel crashing into the phase plate, to reduce the precision required for assembling the encoder kit, to allow large (0.25 mm) shaft end play, and to lower the cost of the code wheels by relaxing their flatness requirement.

Ideally the code wheel and phase plate patterns are concentric. As illustrated in Fig. 4, concentricity offsets between the code wheel and phase plate change the time of when particular windows overlap. In Fig. 4 the windows near area A on the code wheel are early in lining up with the corresponding windows on the phase plate. Code wheel windows near area B are late. If these areas are the locations of the detectors for each quadrature channel, then the effect is an increase in the phase difference between channels. Calculations show this phase shift to be:[1]

$$\Phi_c = 360° \, ens/(2\pi r^2)$$

where Φ_c is the phase shift in electrical degrees caused by eccentricity, e is the offset between the centers of the code wheel and phase plate, n is the number of cycles per revolution, s is the separation between two quadrature detectors, and r is the radius of the code wheel track. This phase shift can result from static or dynamic offsets. A code wheel that is not centered on the shaft causes phase wobble as the shaft rotates. Minimizing the detector separation (2.2 mm) in the HEDS-5000 encoder reduces its phase shift sensitivity to 0.5° per micrometre of offset.

The encoder kit assembly procedure provides for adjustment of static phase offsets. When the body is attached to its mounting surface, RTV (room-temperature-curing silicone rubber) adhesive is applied to the surface and to three mounting screw holes. The screws are tightened to a torque that still allows the body to slide on the wet RTV when firm finger pressure is applied. The recommended assembly procedure is to mount the code wheel on the shaft with epoxy adhesive, snap on the emitter end plate, turn the shaft, and monitor encoder output while moving the body slightly to adjust phase. The epoxy adhesive is stiff enough in its uncured state to maintain the position of the hub during shaft rotation and normal assembly handling. The epoxy also tends to center the hub about an undersized shaft. After a room temperature (or oven) cure, the assembly withstands shock, temperature cycling and other environmental hazards.

Optoelectronic Modules

The paired emitter/detector modules in the HEDS-5000

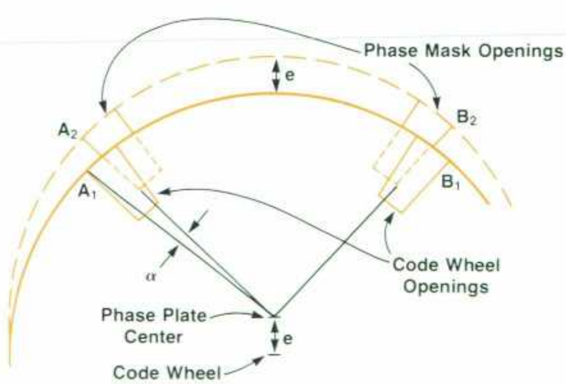

Fig. 4. *Concentricity phase shift error. If the centers of the code wheel and phase plate are separated by a distance e, this shifts the angular location for maximum transmission through the code-wheel/phase-plate openings by an angle α. This shift changes the timing and hence the phase.*

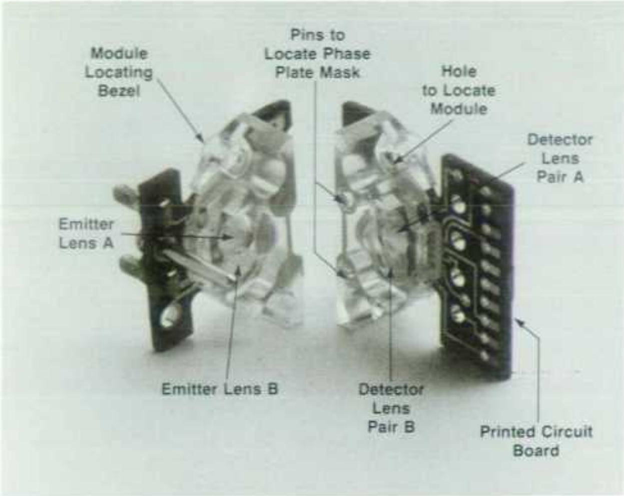

Fig. 5. *Emitter (left) and detector (right) modules for the HEDS-5000. Each module uses a clear polycarbonate lens block to focus and collect the light from the LED.*

encoder are designed to minimize encoder errors by providing good collimation and narrow spacing between the optical paths of each channel. Considerations of cost and reliability led to the additional feature of an integrated detector circuit that can be used without requiring individual gain adjustments.

A photograph of these modules is shown in Fig. 5. The emitter and detector modules are each built around an injection-molded clear plastic lens block. Molded into each lens block is an array of precision optical surfaces and several mechanical alignment features. The polycarbonate lens material withstands temperatures up to 100°C. The lens block is attached by an adhesive to a printed circuit board containing precisely placed LEDs or detector ICs so that they are sealed in a closed cavity behind the lenses.

The emitter lens block includes an array of three lenses, each with its own LED. (The third lens is for a reference pulse that will be included in other products in this family.) The degree of collimation of the emerging light beam depends on the size of the light source and the focal length of the lens. The LED has a 0.18-mm-diameter emitting area, which is a compromise between the desire for a small light source and a large amount of flux with good reliability. A GaAsP (gallium arsenide phosphide) epitaxial emitting layer is used on a light-absorbing GaAs substrate to prevent light from being emitted by the rest of the emitter chip. The focal length of the emitter lenses is 1.8 mm. This, combined with the 0.18-mm-diameter source, limits the angular spread of the beam to 0.1 radian.

Each emitter collimating lens has two aspheric surfaces. The use of two aspheric surfaces allows the lens to be corrected for spherical aberration and to obey Abbe's sine condition. Such lenses are called aplanats.[2] The emitter lenses have a high numerical aperture of 0.7 (the f-number in this particular case is also 0.7). This allows transmission of 50% of the emitted light. In addition, satisfaction of the sine condition causes the light to be uniform in intensity, or very nearly so, over the entire output aperture. This was done to allow phase plates of different geometries to be used. The only requirement for balance is equal areas in the two halves of the phase plate that masks the differential detectors.

Corresponding to each emitter lens is a split pair of detector lenses. Thus there are six lenses on the detector module. Each detector lens pair operates to collect the light passing through the code wheel and phase plate and focus it onto the two small photodiodes on the detector IC. The optical axes of the two detector lenses are separated by the same distance (0.64 mm) as the spacing between the two photodiodes. Pins on the front face of the detector module insure alignment of the phase plate openings to each detector lens pair. Besides the photodiodes, each detector IC contains a pair of matched amplifiers and a low-offset comparator. Production history has shown the typical imbalance between the two detector channels to be about 7% which contributes about 7° to the pulse-width error.

Detector IC

The encoder and its detector IC were designed together.[3] Photodiode size, 0.6-mm-square, was determined by the size of the focused image of the LED source, plus an allowance for assembly tolerances. The size of the photodiodes affects the speed and overall IC size. Detector sensitivity interacts with LED power consumption and reliability. A sensitive detector allows lower drive current in the LED, resulting in lower operating temperature and longer life. Unfortunately, sensitivity and speed are conflicting goals, so a satisfactory compromise had to be reached.

Other requirements were that the detector should be push-pull and operate from a single unregulated supply. Power requirements were limited because some encoder applications may be battery powered. Because of electrical noise generated by motors and other sources and the length of the encoder's cable, the detector would have to do without the luxury of a clean, well regulated power supply.

The detector has both digital and analog output signals. The digital output is directly usable by digital controllers, and is all that is needed for most applications. Velocity data is obtained by timing the interval between digital transitions. Some systems need a velocity update more often, so analog processing must be used. Continuous velocity information is available by differentiating the analog position signal. Although additional position resolution can be achieved by interpolation, it is usually better to increase the code-wheel slot count if higher resolution is needed.

The two differential photocurrents are combined to produce an analog signal similar in shape to either photocurrent, but independent of LED brightness. The analog output is a current source rather than a voltage output because it is desirable to have the signal swing between positive and negative values. With a single power supply, a voltage output would have to be offset from zero, and the amount of offset would have to be known to the user as a function of temperature. A current output, however, can act as a source or sink with zero current indicating equal light intensities. A current output also avoids the voltage output problem of the high current needed to drive a capacitive load at high frequencies. The only requirement of the HEDS-5000 is that the user hold the analog output at a fixed voltage and measure the current into and/or out of the encoder. This is

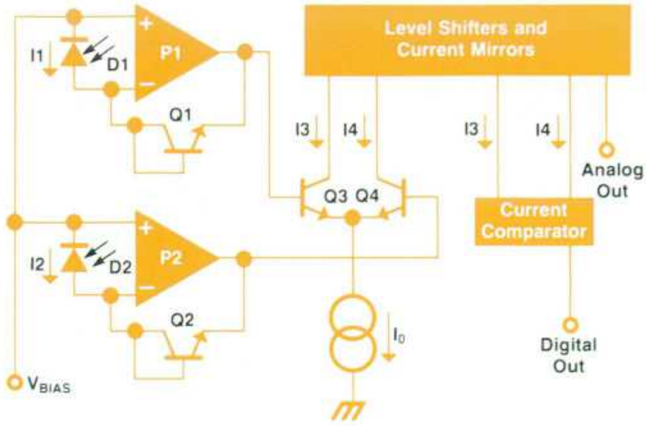

Fig. 6. *Simplified schematic of the detector IC.*

easily accomplished by a transimpedance amplifier.

The detector IC is organized as shown in Fig. 6. Photodiodes D1 and D2 operate at zero bias into preamplifiers P1 and P2. The differential pair Q3 and Q4 compares the preamplifier output voltages and produces currents I3 and I4. The detector's analog output is the difference between I3 and I4. The logical output is derived by comparing replicas of the two currents.

The encoder's analog output current is a triangular wave, with the straight ramp part of each cycle proportional to shaft angle. The photocurrents I1 and I2 are proportional to shaft rotation, but also vary with LED source brightness. Independence of LED light output is accomplished by a log-difference-antilog sequence, which is the algebraic equivalent of division, to get the ratio of the two photocurrents. To a first approximation, the analog output current I_{out} follows the equation:

$$I_{out} = I_0 \left[\frac{I1-I2}{I1+I2} \right]$$

The preamplifiers use the diode-connected transistors Q1 and Q2 as their feedback elements. Each preamplifier output is the logarithm of its photocurrent because of the logarithmic current-to-voltage characteristic of Q1 and Q2. The differential pair, Q3 and Q4, serves the combined purpose of subtraction and antilog functions. The log and antilog functions are complements of each other because transistors Q1 through Q4 have matched geometries. Currents I3 and I4 are proportional to the original photocurrents, but sum to I_0, nominally 50 μA. I3 and I4 are subtracted by current mirrors* to produce the analog output. The power supply determines the compliance limits of the current mirrors, and the external circuit must hold the output node at a fixed voltage between V_{BE} and $V_{CC}-V_{BE}$.

A comparator operates on replicas of I3 and I4 to form the detector's logic output. The comparator includes hysteresis to avoid instability or an ambiguous output state if the shaft should stop exactly at a transition. With hysteresis the output has a slight preference for its present state so the shaft must rotate slightly past the theoretical transition before the output actually changes. The displacement of the signal from the ideal is not a significant source of error. Nevertheless the amount of hysteresis should be as independent as possible of temperature and process variations.

The detector IC is 1.5 mm square and requires 1 mA from a single 5V supply. By having matched push-pull channels, the IC achieves good rejection of electrical noise. Extra circuitry is also included to allow initial testing of the IC in wafer form without using precision light sources.

*Editor's note: A current mirror is a device configuration whose output current is maintained at the same magnitude as the controlling input current independent of output load. Here I4 is the input current and the output current of the current mirror is combined with I3 to subtract one current from the other.

Code Wheel and Phase Plate

The code wheel manufacturing process was chosen as the best compromise from a long list of wishes. The ideal code wheel should have a low moment of inertia, be rugged and stable in any environment, have no mechanical resonances, offer high resolution, and be inexpensive.

A 500-count code wheel for the present encoder is about 25 mm in diameter and 40 μm thick, and has bars and slits about 65 μm wide.

Code wheels and phase plates are made by an electroforming process. A negative image of the desired part is made of thick photoresist on a conductive substrate. Then a nickel alloy is plated on the exposed areas of the substrate to form the desired piece and the photoresist and substrate are removed.

It is important that the code wheel be accurately centered on the shaft. The electroforming process is convenient in this respect because the center hole is automatically defined by the same process step that defines the slits.

Case and Cable

The design goals for the case of the HEDS-5000 were low manufacturing cost, precise assembly, protection from the outside environment, ease of use and repair, and thermal stability. These goals are met by using a set of molded glass-filled nylon parts as shown in Fig. 3. Screws are used to fasten the detector body to the end of the motor. The rest of the connections are made by molded-in snaps and glue joints. The use of precision-molded plastic case parts allows easy alignment of the emitter and detector modules. Other molded-in features provide strain relief for the connection cable, support for the phase plate, and guide holes for the resistor and pin that electrically connect to tiny sockets in the emitter module.

Ribbon cables are used in the HEDS-5000 because of their compact size, low cost and ease of connection with insulation displacement connectors. The ribbon cable is easily soldered into the detector module's printed circuit board because the cable's individual wires readily align with a series of uniformly spaced holes in the board.

Testing

The product cannot be tested in final assembled form before delivery to the customer because the customer performs final assembly. Thus each of the three kit items is separately tested for function and accuracy. Accuracy limits are set to assure high yield (typically 99%) at customer assembly.

Detectors are tested on a computer-controlled test fixture that accurately injects light beams into the detector lenses. This tester can test the outputs under a variety of optical conditions. Code wheels are tested in an actual encoder made of a selected detector with a precision spindle and collimated light source. Emitters are tested for light output, uniformity, and aiming. Besides measurements directly related to guaranteed parameters, several other electrical characteristics are tested to be sure they fall in the normal range.

Reliability

The expectation that wide code-wheel gaps, low emitter drive currents and all solid-state construction would provide a highly reliable encoder design has been verified. Groups of encoder kits, assembled onto low-cost dc motors by inexperienced operators, are undergoing environmental life tests. So far, one group has experienced 300,000 device hours of power operation (motor shaft rotating) at 85°C without failure. Another group of 12 units has operated 200 days while subjected to temperature cycling from −7°C to 65°C at 95% relative humidity (MIL-STD-202E, method 106D-modified) without failure.

Acknowledgments

The authors would like to thank Tom Fajardo, Fred Goodman, Mat Stein, Jim Casciani, and Gerd Hellman for package development, Eddie Weaver for optical design, Bill Loesch for manufacturing engineering, Walt Heinzer and Henry Chen for reliability testing, and John Sien and Ron Sandretti for marketing.

Mark G. Leonard

Mark Leonard joined HP in 1975 with several years of experience in failure analysis, diagnostic programming, and teaching software. Mark initially worked on reliability at HP and now is a development engineer. He is the author of an article on the detector IC used in the HEDS-5000 and is named inventor on two patents on this IC. Mark was born in San José, Costa Rica and attended Macalester College in St. Paul, Minnesota where he earned a BA degree in physics in 1965. He is a member of the IEEE and a registered professional engineer in California. Mark is married, has three sons, and lives in Los Altos, California. He spends most of his spare time working around his home when he isn't involved with woodworking or photography.

Howard C. Epstein

Howard Epstein was born in Los Angeles, California and attended California State University at Los Angeles where he earned the BA (1965) and MS (1975) degrees in physics. Before joining HP in 1976, he worked on the development of transducer products. At HP Howard designs optical shaft encoders and was project leader for the HEDS-5000. He is the author of three papers on mechanical sensor design and is named as an inventor on two optical encoder and three piezoelectric transducer patents. Howard is a registered professional engineer in California and is on the board of directors of the Network for Conscious Judaism which sponsors adult religious study. He is married, has three daughters, and lives in Los Altos, California. Howard enjoys playing handball and bicycles 12 miles to work.

John J. Uebbing

John Uebbing was born in Chicago, Illinois. He received the BSEE degree from the University of Notre Dame in 1960, the MSEE degree from the Massachusetts Institute of Technology in 1962, and the PhD degree from Stanford University in 1967. He came to HP in 1973 with several years of experience working with electron spectrometers and III-V semiconductor photocathodes. At HP John has been a project leader for alphanumeric displays and manager of the packaging and emitter detector groups in HP's Optoelectronics Division. He is now working on advanced displays in HP Laboratories. John is the author of several papers on photocathodes and optoelectronic devices and is a member of the Society for Information Display. John lives in Palo Alto, California, is married, and has two children. He enjoys backpacking, sailing and playing bridge, and is interested in religious education.

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ABRIDGED SPECIFICATIONS
HP HEDS-5000 Encoder Kit

RECOMMENDED OPERATING RANGE:

Parameter	Symbol	Minimum	Maximum	Units	Notes
Temperature	T	−20	85	°C	Noncondensing
Supply Voltage	V_{CC}	4.5	5.5	V	Ripple < 100 mV p-p
Code Wheel Gap			0.8	mm	Nominal gap = 0.43 mm when shaft is at minimum gap position.
Shaft Perpendicularity Plus Axial Play			0.25	mm	
Shaft Eccentricity Plus Radial Play			0.04	mm	10 mm from mounting surface

ENCODING CHARACTERISTICS:

Parameter	Typical	Units	Notes
Position Error	10	Minutes of arc	1 Cycle = 43.2 Minutes
Cycle Error	3	Electrical degrees	
Pulse-Width Error	20	Electrical degrees	at 25°C, 50 kHz
Logic State Width Error	30	Electrical degrees	at 25°C, 50 kHz

MECHANICAL CHARACTERISTICS:
DIMENSIONS: 28 × 35 × 18 mm
STANDARD SHAFT SIZES: 2 mm, 3 mm, 1/8 in, 3/16 in, 5/32 in, 1/4 in.

PRICE IN U.S.A.: $80.00 in quantities of 10 to 99.
MANUFACTURING DIVISION: Optoelectronics Division
640 Page Mill Road
Palo Alto, CA 94304 U.S.A.

New Plotting Technology Leads to a New Kind of Electrocardiograph

A low-mass, low-inertia plotting mechanism provides high-quality ECGs in a variety of convenient formats.

by Peter H. Dorward, Steven J. Koerper, Martin K. Mason, and Steven A. Scampini

AN ELECTROCARDIOGRAPH is a machine that takes information in the form of bioelectric voltages from a series of sensors, called electrodes, attached to the body and records these voltages for analysis and diagnosis. The records are called electrocardiograms (ECG) and are described in the box on page 20. The electrocardiograph must address many special problems because of where it is used, what it is used for, and who uses it.

The electrocardiograph market is a place of contrasts among users and end uses. Approximately 120,000,000 ECGs are performed every year in the U.S.A. on a wide variety of patients. Routine ECGs establish baseline records for patients. ECGs taken during medical emergencies aid in lifesaving treatment and there is a spectrum of ECGs taken for a variety of reasons in the range between.

Because of the widespread use of electrocardiographs and the importance of the results, users have developed a certain set of expectations with regard to these machines. The U.S.A. and Europe have developed standards of performance, safety, construction and labeling that must be met to sell an electrocardiograph in many countries. Cost of ownership and cost of operation are important elements of an ECG machine. The high cost of equipment has prevented the widespread use of high-trace-quality machines in deference to lower-quality, lower-cost machines. Reliability is important to the repeatability and ready availability of the ECG test. Good record quality and a clear presentation of the data are necessary for the proper interpretation of the ECG.

Fig. 1. *The HP Model 4700A PageWriter Cardiograph is a state-of-the-art machine that records ECG data in a page-sized format with high trace quality. The page format makes it easier to interpret ECG data and file it for future reference.*

Design Considerations

The design goals for the HP Model 4700A PageWriter Cardiograph (Fig. 1) were that the instrument should be easy to operate, portable, reliable, and less expensive to purchase and operate than other existing electrocardiographs with comparable features. The recorder technology (see article on page 3) that was being investigated at Hewlett-Packard's central research laboratories seemed well suited to these design goals. The use of microprocessors also fitted our design needs by allowing the replacement of some hardware with firmware and by making possible a more powerful and flexible instrument.

The recording mechanism is a digitally controlled X-Y plotter (Fig. 2). Therefore it is necessary to digitize the ECG waveforms by placing an analog-to-digital converter (ADC) after the ECG front end. The ECG data also has to be temporarily stored in a memory to enable a single-pen recorder to record multichannel formats.

The new recorder technology allows a great deal of flexibility in specifying the record formats produced by the cardiograph. However, flexibility in an instrument often complicates the operation of that instrument. The design problem therefore becomes twofold: decide what capabilities of the instrument are useful clinically, and implement them in a manner that is easy to operate.

The 4700A uses the traditional operating modes of cardiographs plus several enhancements that draw on the strengths of the new low-mass, low-inertia plotting technology. The results of the new technology are shown by the example in Fig. 3. Note the quality of trace and the annotations that can be added by the 4700A to identify the

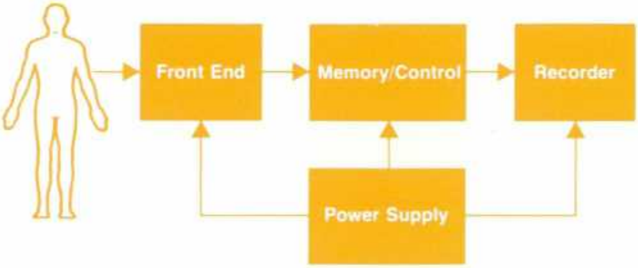


Fig. 2. *Basic block diagram of the 4700A PageWriter Cardiograph.*

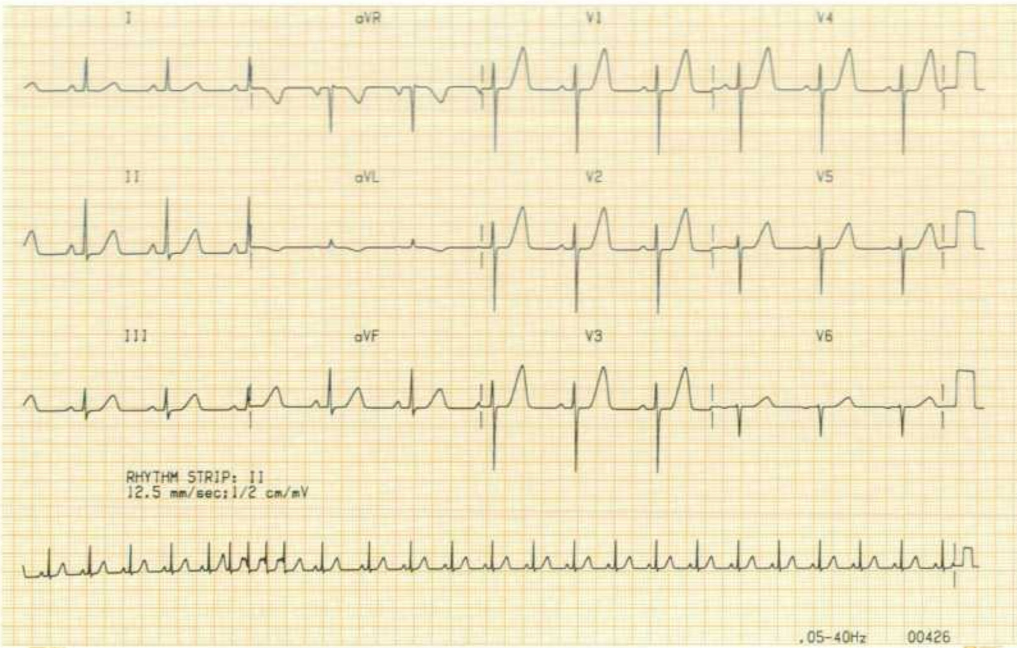


Fig. 3. *The 4700A makes it possible to record both morphology (12-lead) and regularity (rhythm) ECG data conveniently on a single piece of paper (shown here at 48% of actual size).*

various sections of the ECG clearly.

As shown in Fig. 3 the new recording technology allows for the presentation of both morphology (the 12-lead **AUTO** ECG) and regularity (the added rhythm trace) on the same piece of paper. Before the advent of the 4700A, the regularity presentation was often recorded for only a small number of patients because it used additional paper and was not easy to review and file. Now the 12-lead-plus-rhythm ECG can be performed with only a slight additional time at the bedside. This combined record can present the cardiologist much more information about the state of the heart in a very convenient format. Multiple identical copies of the traces can be made by simply pressing a **COPY** key instead of having to repeat the ECG at the bedside. Today consummables, paper costs and waste can be a significant operating cost of an ECG machine. With the 4700A and its **COPY** feature, waste can be reduced significantly. For detailed timing analysis, the rhythm trace at the bottom of the 12-lead ECG can be speeded up to 100 mm/s or a three-channel trace can be taken at 200 mm/s in the **MANUAL** mode.

The **RHYTHM** function can be used with many choices of trace speeds, sensitivities and leads. One format records almost one-half hour of ECG data on a single sheet of paper. This extended format (Fig. 4a) allows less frequent, sometimes more complex and life threatening arrhythmias to be recorded and recognized. Portions of the rhythm trace may be saved during recording by using the **SAVE** key, and later be copied (Fig. 4b), using the **COPY** key, at normal speed (25 mm/s) and sensitivity (1 cm/mV). This allows saved arrhythmias to be reviewed for morphology.

Each of the three primary operating modes of the 4700A (**AUTO**, **MANUAL**, **RHYTHM/SAVE**) has one set of parameters, such as sensitivity, paper speed, and lead selection, that defines the final record. A pull-out card, located beneath the cardiograph, lists the ten formats available (Fig. 5) and gives instructions for their selection. The 4700A uses a 10-position rotary switch to select a format. Each format specifies all of the parameters for each of the operating modes of the instrument. The first five formats are fixed. The remaining five are altered by using the **F** (function) and **P** (parameter) keys on the control panel (see Fig. 6) and are stored in a nonvolatile memory.

System Design

The 4700A consists of four major elements as shown in Fig. 2. The ECG front end is responsible for acquiring the ECG from the patient while also isolating and protecting the patient from electrical shock hazards. It converts the signals into a digitized ECG waveform. The ECG samples are passed to the controller, which stores the data in a 16K × 12-bit dynamic RAM array and passes the data on to the recorder when it is ready to plot a new point. The controller is based on a 6800 microprocessor and contains 36K bytes of firmware to implement the various operating modes of the instrument. The recorder is controlled by a 6801 microprocessor and two custom servomechanism controllers.

The power supply design uses a switching supply to improve efficiency. The switching frequency is chosen so that modulation of the frequency used in the ECG front end is avoided. The ac power supply module can be configured by jumpers to operate at any of the line voltages and frequencies used throughout the world.

The plastic enclosure is designed to be pleasing to the eye, rugged, utilitarian, and low cost. The plastic cart forms an efficient work surface with letter trays for paper and record storage and large storage bins and surfaces located at working height and underneath. The cart and the package are designed to protect the instrument and improve reliability in the rugged-use environment of a hospital.

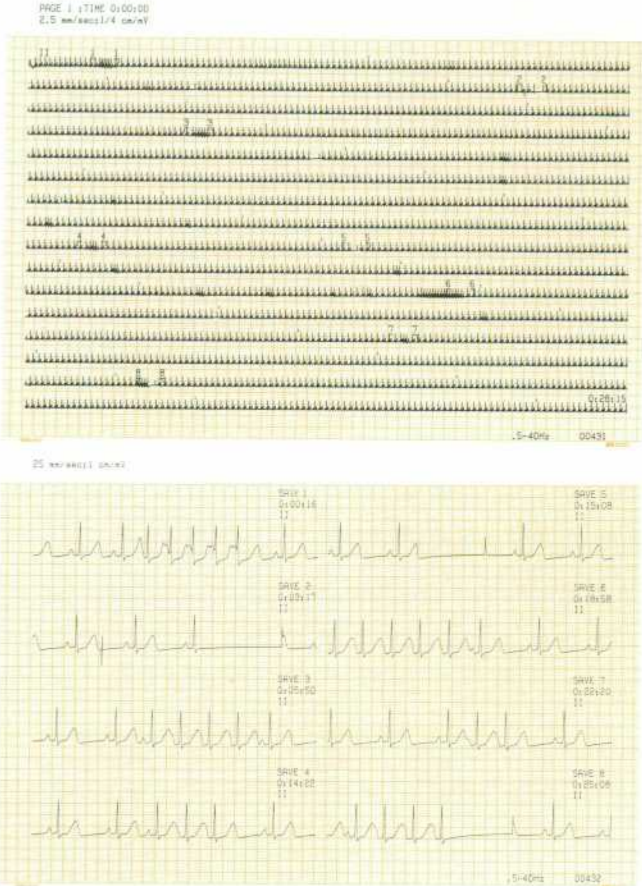


Fig. 4. *Examples (shown here at 30% of actual size) of various trace formats that are possible by using the 4700A. (a) The extended* ***RHYTHM*** *function can record almost one-half hour of ECG data to detect less frequent arrhythmias. (b) Portions of the rhythm trace can be saved and copied later at a different speed and sensitivity.*

CHOOSING ECG FORMATS

FORMAT SWITCH POSITION	OPERATING MODES		
	AUTO 12 LEADS Plus RHYTHM Strip	MANUAL 3 LEADS	RHYTHM SINGLE LEAD with SAVE
1	12 LD No RHYTHM Strip	I, II, III	II 5 sec of II
2	12 LD II	aVR, aVL, aVF	II (½) 5 sec of II
3	12 LD II (½) 12.5mm/sec	V1, V2, V3	II (½) 12.5mm/sec 10 sec of I, II, III
4	12 LD II (½) 5mm/sec	V4, V5, V6	II (¼) 5mm/sec 1.5 sec of II
5	12 LD II (¼) 2.5mm/sec	SPECIAL LEADS ☐ II, aVF, V5 ☐ ☐ FRANK XYZ	II 2.5mm/sec 5 sec of II
6	12 LD V1	V1, V2, V3 UPPER PAGE	III (¼) 2.5mm/sec 5 sec of III
7	12 LD V1 (X2) 50mm/sec	V4, V5, V6 LOWER PAGE	aVF (¼) 2.5mm/sec 10 sec of aVF
8	12 LD V1 (X2) 100mm/sec	SPECIAL LEADS 50mm/sec	V1 (¼) 2.5mm/sec 5 sec of V1, V2, V3
9	12 LD (½) II (½) 12.5mm/sec	SPECIAL LEADS (X2) 100mm/sec	V2 (¼) 2.5mm/sec 5 sec of V1, V2, V3
10	12 LD (½) No RHYTHM Strip	SPECIAL LEADS (X2) 200mm/sec	V6 (¼) 2.5mm/sec 5 sec of V4, V5, V6

NOTE: Speed is 25mm/sec unless otherwise noted. Sensitivity is 1cm/mV unless noted as (¼, ½ or X2).

Fig. 5. *An operating card is supplied with the 4700A to aid the user in selecting and modifying the ECG format. Additional information (not shown) provides operating instructions and interprets displayed error codes.*

Fig. 6. *Control panel of the 4700A. The recording function is selected by using the keys on the left and the format can be selected and/or modified by using the display, keys, and rotary switch on the right.*

Connection to the Patient

The function of the front end of the 4700A is to combine, amplify, and convert the voltage potentials generated by the heart on the surface of the patient's body to a digital form. Considerations involved in the design of the 4700A front end are the need for high input impedance, low noise at high source impedances, large dynamic range, total voltage gain of several thousand, analog-to-digital conversion, patient safety, rejection of large contaminating signals and protection of the circuitry during the application of defibrillation equipment to the patient.

Patient safety involves the sensitivity of the heart to very small levels of 50/60-Hz ac current. Small ac currents flowing through the heart muscle can cause fibrillation, a condition in which the electrical pacing system of the heart is no longer in control. Random contractions of the muscle occur, resulting in loss of pumping action and eventually death. Without proper design the instrument connection to the patient could serve as either a source of this current (if the electrocardiograph circuitry developed a voltage relative to earth ground and the patient was in contact with earth ground such as the metal frame of a bed), or a sink for the current (if the patient came in contact with a power line and the electrocardiograph circuitry was earth grounded). By using dielectric material to isolate all circuitry connected to the patient and minimizing the resulting capacitance, these hazards can be eliminated.

In the 4700A, this is done by surrounding the isolated circuitry with a plastic enclosure and transferring power and signals via transformers (Fig. 7). Power transfer at power line frequency and baseband transmission of the analog signals would require impractically large transformers with far too large interwinding capacitances. Instead, power transfer and modulation of the analog channels is done at a frequency of 100 kHz to allow the use of small, low-interwinding-capacitance transformers. The total capacitance between the isolated section and the rest of the instrument, which is ground-referenced, is less than 200 picofarads. This insures that no more than 10 μA rms of current will flow for an ac voltage differential of 120V rms.

The heart-generated signals on the surface of the patient's body exist as differential voltages on the order of a few millivolts. Most of their spectral content lies in a band from 0.05 Hz to 100 Hz. Besides these desired differential voltages, there may be large (10V rms is not uncommon) common-mode signals that result from capacitive coupling of the patient to the omnipresent 50/60-Hz ac power wiring. A high degree of rejection of these power-line-induced signals is required for usable ECG recording. The desired rejec-

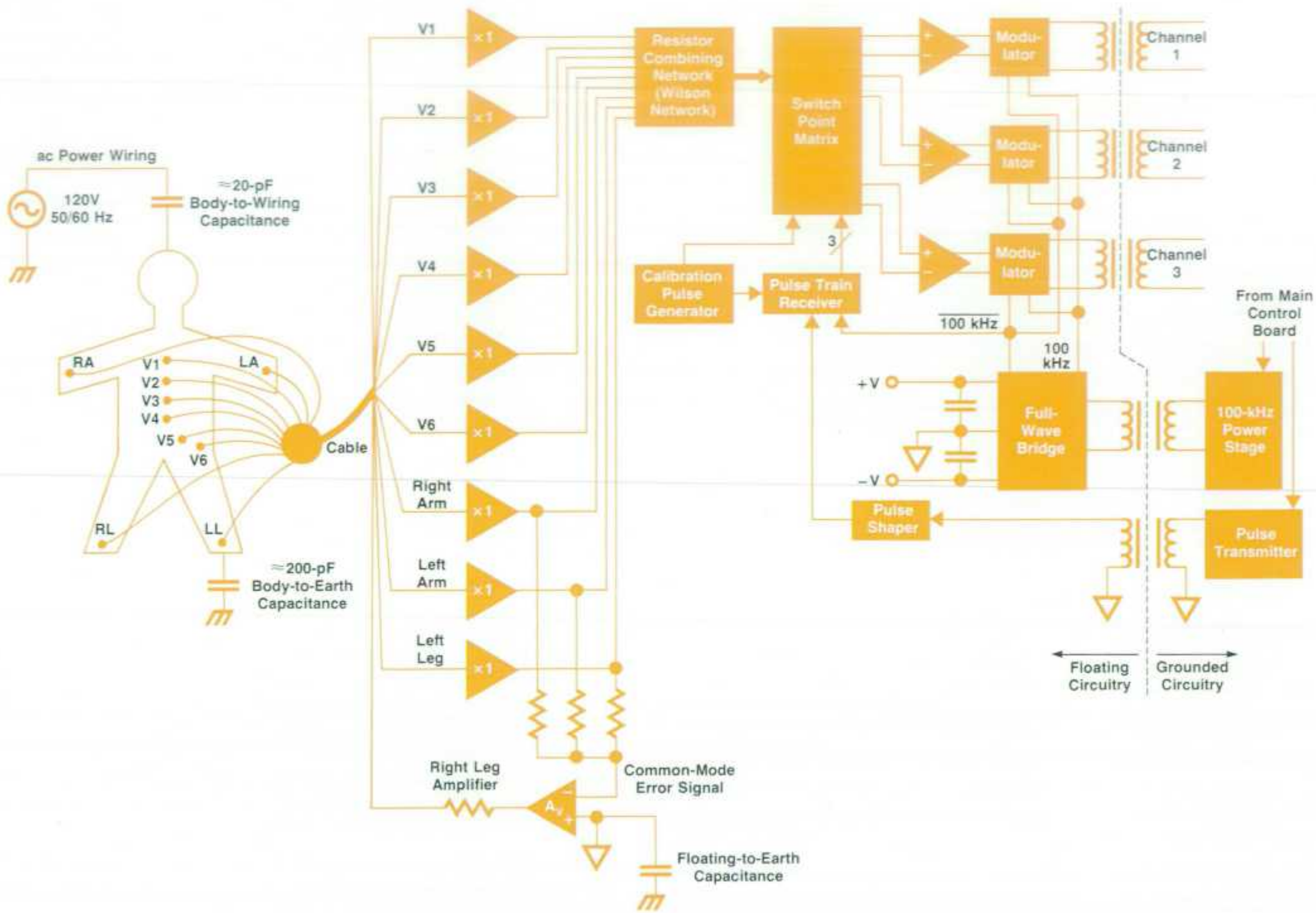


Fig. 7. *Diagram of front-end electronics showing the connections to the patient on the left and the isolation boundary on the right. Signals and data are communicated across the isolation boundary to the rest of the 4700A by using high-frequency, low-interwinding-capacitance transformers.*

tion is achieved when the patient-connected circuitry is at the same potential as the common-mode signal.

Two approaches are used to obtain this equipotentiality. One is to shield the patient cable and isolated circuitry with the common circuit point of the isolated front end (called the guard). The other is to send back to the patient a cancellation current derived from any common-mode signal arriving at the isolated front end. This closed-loop system is called the "right leg drive," the injection point for the cancelling current being the right leg. In this configuration the patient becomes in effect the virtual ground (or in this case, virtual guard) of a feedback amplifier. The input signal is the ac-power-line common-mode signal. Any common-mode potential difference between the isolated circuitry and the patient is driven to zero (for a theoretically infinite-gain right-leg amplifier) by the feedback.

Defibrillation is the application of a high-voltage pulse to the patient's chest in an attempt to resynchronize the heart by interrupting the random muscle activity of fibrillation to let the natural pacemakers resume pacing. The amplitude of this pulse can be as high as 8,000 volts and it can last several milliseconds, with a delivered energy of up to 400 joules. The electrocardiograph must be able to survive this procedure.

The differential components of the defibrillation pulse that appear at the ECG electrodes are clamped by limiting networks in the front end of the 4700A and dissipated by resistors in series with each electrode lead in the patient cable. A limiting network consists of a neon bulb followed by resistor and diode clamps. The common-mode component (referenced to ground) is blocked by the special design of the isolation transformers rated for 25 kV, and by the convoluted plastic enclosure around the isolated circuitry that provides a minimum air gap of 2.5 cm to ground-referenced circuitry. The 100-kHz square-wave signal that powers the isolated circuitry also serves as the switching drive to the analog-signal modulators. Control data for the isolated circuitry is sent in a serial pulse train via a separate low-capacitance transformer. The appropriate ECG waveform is selected by the switching matrix, modulated by the 100-kHz signal, and coupled via a low-capacitance transformer to one of the three channels as shown in

Fig. 8. Each channel processes the signal to remove the 100-kHz modulation and convert the analog waveform into digital data.

Recording Technology

Exploded views of the paper drive and pen drive mechanisms are shown in Fig. 9 and Fig. 10. The paper is driven by two grit-coated wheels which in turn are driven by a dc servo motor through a reinforced toothed belt. The pen cartridge snaps into a carriage which is moved in a direction perpendicular to the paper travel by an identical motor-encoder through a 71-cm toothed belt.

Adapting the new plotting technology to an ECG recorder presented two basic challenges: to use a digital, point-to-point, X-Y plotter to record a random analog waveform accurately, and to interface to a nontechnical user who requires ease of use and speed.

The digitized ECG waveform arriving at the recorder is characterized by very short (<1 mm) line segments. The plotting mechanism halts between segments, resulting in both axes constantly accelerating without reaching maximum velocity.

Plotting this waveform, the first concern is to produce a trace in as close to real time as possible, so maximizing acceleration is an important goal. But a second competing concern is the need to limit power consumption because the instrument case is closely packed and unventilated. Both requirements point to the need for a low-mass drive system with efficient motors.

The design tradeoffs are better seen by noting that, in an

What Is an Electrocardiogram?

An electrocardiogram (ECG) is a test used widely to assess the condition of the heart noninvasively. The ECG is used to evaluate the status of the heart's conduction system, the status of the muscle and, indirectly, the condition of the heart as a pump. The ECG is a graphical presentation of the bioelectrical activity (voltage) of the heart muscle and an ECG machine (electrocardiograph) is a recording voltmeter.

The heart (Fig. 1) has four chambers called the right and left atria and ventricles. The right atrium receives venous blood from the body. It delivers the blood to the right ventricle where it is pumped to the lungs, picks up oxygen and goes to the left atrium. The left atrium pumps the blood to the left ventricle where it is pumped throughout the rest of the body and returned to the right atrium.

All of the pumping actions are in response to electrical impulses that cause the heart to contract. These pulses originate in the S-A (sino-atrial) node. The S-A node or "pacemaker" acts like a clock by generating a regular stream of pacing pulses that contract the atria repeatedly to force blood into the ventricles.

Once the atria are contracted fully, the electrical impulse is picked up by a high-speed conduction system which excites, or depolarizes the ventricles. This conduction system starts with the A-V (atrio-ventricular) node. The A-V node receives the impulse from the atria and passes it to the Bundle of His, the Bundle branches and the Purkinje fibers. They speed the impulse rapidly throughout the right and left ventricles, initiating a coordinated contraction and efficient pumping of blood to the body.

The ECG waveform (Fig. 2) has several parts which depict the action of the heart cycle. These parts are the P, Q, R, S, and T waveforms which together are called a complex.

The P wave is caused by the depolarization and subsequent contraction of the atria. The QRS complex is the depolarization of the ventricles. The T wave is the repolarization of the ventricles after which the heart muscle is ready for the next pace pulse from the S-A node.

Irregularities in the shape (morphology) of the PQRST complex indicate heart muscle abnormalities. Irregularities in the timing of the waveforms (rhythm) either within one complex or between several complexes indicate conduction abnormalities. Therefore, the shape and regularity of the ECG waveform are both necessary in making a proper diagnosis of the condition of the heart. Normal variations and medically important ECG conditions make the practice of diagnostic ECG interpretation a complex and hard-learned profession. Therefore, presenting the ECG to the reviewing physician in a convenient, clear, and complete form is important and can make the interpretation easier.

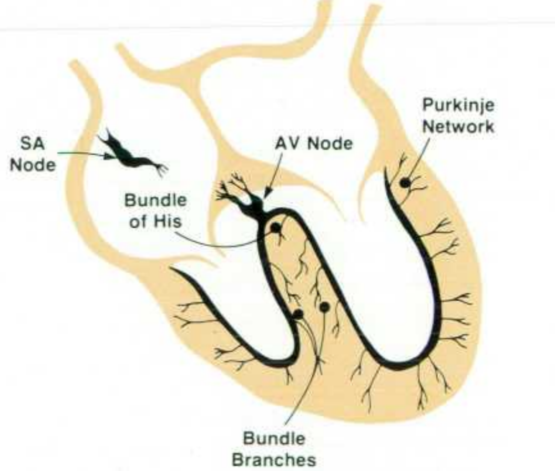


Fig. 1. *Cross-sectional diagram of the heart showing the atria, ventricles, and other features referred to in the text.*

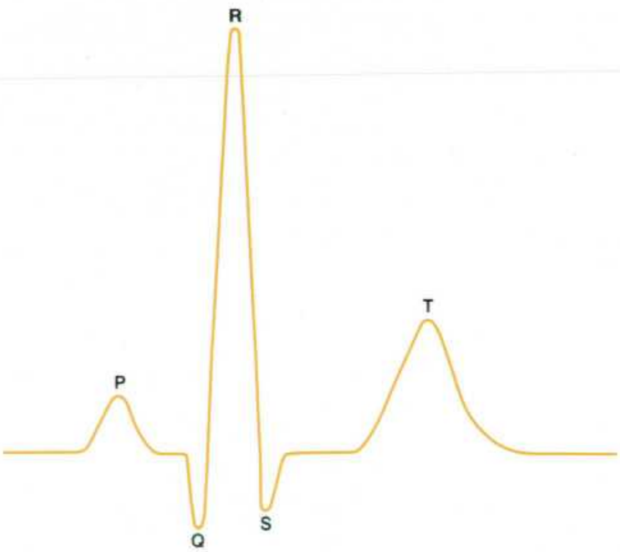


Fig. 2. *Typical ECG waveform for one heartbeat.*

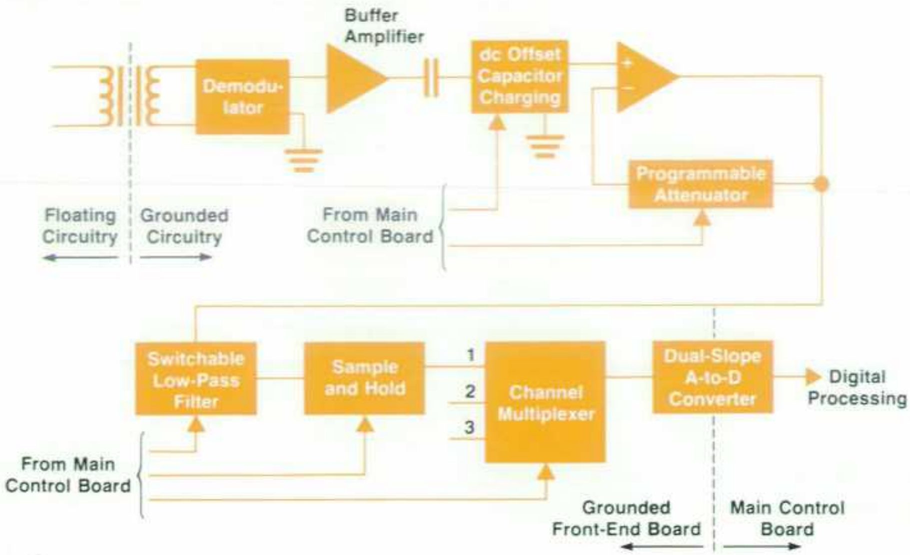


Fig. 8. *Block diagram of one of the three ECG data channels in the 4700A. The measured bioelectric voltage is amplified and filtered by this circuit and then converted into digital data that is stored and processed by a microcomputer for output on the ECG record.*

acceleration-limited situation where friction is a minor portion of the load, the plotting time is proportional to the inverse of the square root of the acceleration. That is,

$$t \propto \sqrt{1/a} \qquad (1)$$

where the acceleration is

$$a = F/m \qquad (2)$$

Thus,

$$t \propto \sqrt{m/F} \qquad (3)$$

where m is the mass and F is the force applied by the drive motor. For the low inductance and relatively low-speed motors used in the 4700A

$$F = KI \qquad (4)$$

where K is the motor force constant and I is the motor current. The instantaneous power P is given by

$$P = I^2R \qquad (5)$$

where R is the resistance of the motor. By manipulating equations (3) and (4) into (5), we can derive

$$P \propto \frac{Rm^2}{K^2t^4} \qquad (6)$$

Therefore, the total energy for a plot is

$$E = \int P dt \propto \frac{Rm^2}{3K^2t^3} \qquad (7)$$

From equations (3) and (6) it can be seen that by decreasing the system mass the plotting time can be decreased and the power can be decreased substantially. In addition, in a system of fixed mass, equation (6) shows that to halve plotting time the instantaneous power must be increased sixteen times and the total energy is increased eight times. Usually, this is not a practical approach. Designing the dynamic system then becomes a matter of minimizing mass and choosing a motor that minimizes Rm^2/K^2.

Step motors have relatively high moments of inertia for a given torque capability and require position feedback in a precision servo system. The alternative is a dc servo motor, either of conventional iron armature design or one with an ironless rotor and basket armature. These offer similar efficiencies and surprisingly similar inertias. The latter design is used in the 4700A because it lacks the cogging associated with the poles of an iron-rotor motor. This behavior can show up as periodic errors during plotting.

The servo system design is straightforward, consisting of position feedback with the addition of velocity feedback to give the system damping. The implementation is novel, however. A high-resolution optical encoder (see article on page 10) is attached to the motor as the feedback element. The entire decoder, servo and drive electronics are implemented digitally as a single integrated circuit chip (see box on page 8). This design originated at Hewlett-Packard Laboratories and was implemented by HP's Corvallis Division. This chip drives the motors through a Darlington power transistor stage. It allows substantial space savings over a discrete linear design and makes the use of an incremental encoder possible. The encoder outputs a pulse each fraction of a degree of motor rotation and offers a large improvement in reliability compared to the slidewire resistors often used for position feedback.

As with most improvements there are tradeoffs. In this case using a shaft encoder requires that the drive elements and the loads (paper drive and pen carriage) be open-loop. Thus, errors in their position with respect to the motor shaft go uncorrected. To keep this section accurate and repeatable a toothed (timing) belt and small (10-tooth) pinion are used to drive the paper and carriage. This combination offers almost the only technique for achieving adequate pen and paper resolution without resorting to a gear reduction (which brings its own problems of cost, size, and hysteresis). The pinion tooth profile is specially designed to minimize backlash when reversing direction.

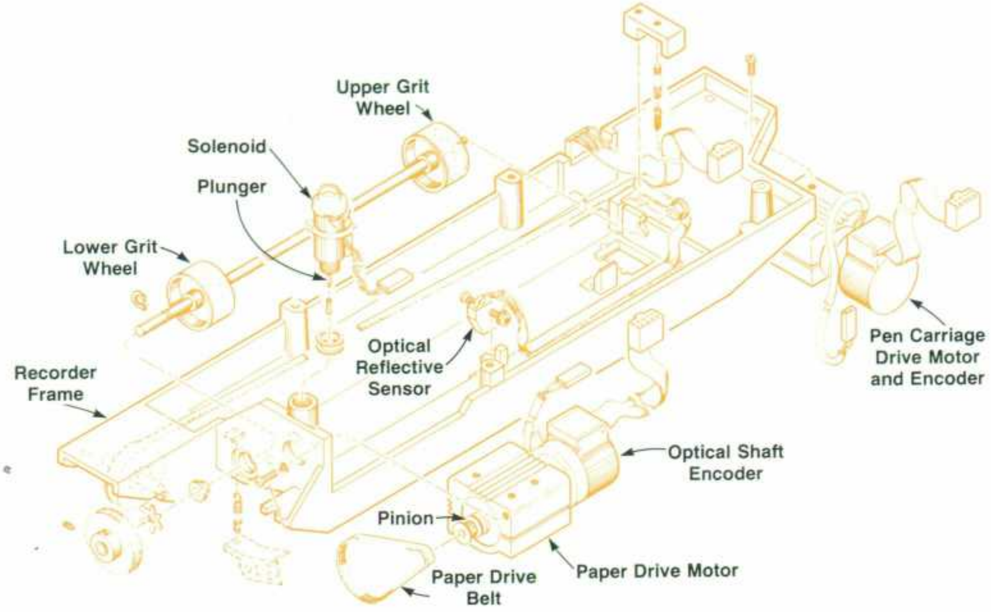


Fig. 9. *Paper drive mechanism. The paper is moved along the Y-axis by two grit-covered wheels located on opposite edges of the paper. These wheels are driven by a digitally controlled dc motor.*

The two belts are reinforced to minimize their compliance. The longer pen carriage drive belt is made of Kevlar™ fibers and the short paper drive belt is made of polyester so that the overall compliances of the two are comparable.

The drive rollers (Fig. 9) consist of turned hubs with adhesive-backed strips of silicon carbide paper applied around their circumference. Gluing abrasive particles to the hubs was considered, but the abrasives industry technology for producing uniform abrasive sheets, with individual particles ruggedly mounted and with points oriented out, provides the most reliable manufacturing scheme.

Two small pinch rollers (Fig. 10) clamp the paper to the grit drive rollers. The pinch rollers are made of a self-lubricating plastic which maintains its shape while pressed against the paper. This is critical because the supporting shaft for these rollers also supports seven idler wheels which roll over the paper surface and are spaced 0.3 mm above the platen. They are made of a hydrophobic plastic with beveled edges so they will not pick up wet ink. All nine rollers force the paper to curve as it passes over the writing surface. This insures complete contact with the writing surface and a well defined paper surface from which the pen can lift. This scheme takes the place of a vacuum holddown which would have been impractical given the space limitations of the 4700A.

A series of ridges on the 4700A platen perpendicular to the paper travel minimizes drag caused by static buildup. Charges are still generated, but the contact area is small enough to minimize static attraction which would cause drag. The plastic is not conductive so the charge bleeds off gradually.

To simplify assembly, the recorder frame (Fig. 9) is a single molded part of 30% glass reinforced polycarbonate with mounting details for various assemblies. The stability of the material is such that flatness across the writing surface is maintained to better than 0.1 mm over a distance of 200 mm.

The carriage and pen cradle (Fig. 10) are molded of glass and Teflon™-loaded polycarbonate. This is an excellent bearing material against a properly ground rod and allows the slide bearings and the knife-edge bearings supporting the pen cradle to be molded-in details of the carriage. Although some other Teflon-loaded plastics have slightly better wear characteristics, polycarbonate provides the best dimensional stability for molding precision bearing holes.

Molded knife-edge bearings, which allow the pen cradle to pivot and lift the pen, were chosen for their low friction and lack of play when loaded. The pen cradle is rotated by a simple electromagnet, raising the pen. A 0.13-mm thick polyurethane pad is mounted between the mating magnet surfaces. This reduces noise caused by the pen lift (the pen lifts about twelve times per second during character plotting) and insures that residual magnetism will not latch the pen in the raised position after the magnet current is removed.

The last item on the carriage is an optical sensor which is capable of detecting the paper's leading edge to an accuracy better than 0.1 mm. This is part of the mechanism that automatically aligns the paper after it is inserted. The solenoid and a second optical sensor shown in Fig. 9 constitute the remainder of this loading mechanism.

To understand the paper loading/straightening scheme we'll follow a sheet through the process. Paper is inserted until its leading edge covers the hole indicated in Fig. 10, tripping the reflective sensor (Fig. 9). This activates the drive rollers in a direction that pulls the paper in as it engages with them. The carriage moves at this time so that the optical sensor on it is positioned at the top (near the carriage motor) of the platen. When this sensor detects the paper's leading right edge the paper drive motor halts and the carriage travels to the lower side of the platen. The paper again moves (the direction determined by the presence or absence of paper as detected by the sensor on the pen carriage) until the leading edge is found at this lower platen location. The direction and magnitude of this last move gives a measure of the paper skew and is stored by the 4700A's processor.

The straightening process is accomplished by activating the solenoid (Fig. 9) located near the lower end of the

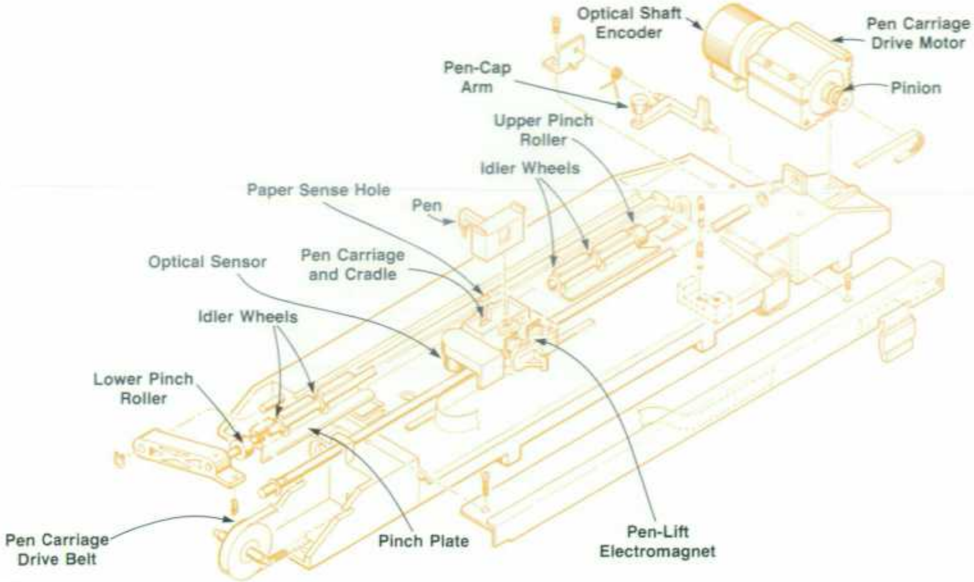


Fig. 10. *Pen drive mechanism. The pen is mounted in a carriage that is moved back and forth along the X-axis by a toothed belt driven by a digitally controlled dc motor.*

platen. Its plunger passes through the platen from below and pins the paper to the underside of the pinch plate. This plate is attached to the rod that supports the pinch rollers and idler wheels. Thus, the solenoid force also lifts the lower pinch roller so that the lower grit-drive roller no longer engages the paper.

Finally, by driving the paper axis motor a distance determined by the previous skew measurement, the other grit-drive roller at the top of the platen forces the paper to rotate about the solenoid tip. This aligns the paper with the recorder axes.

The alignment process ends by disengaging the solenoid, simultaneously reengaging the lower grit-drive roller. The carriage-mounted detector scans to the lower edge of the paper to determine its vertical position and automatically sets up the paper coordinates.

This scheme contributes to the second major goal of the project, simplifying the human interface. Paper can be accepted with large misalignment and in less than two seconds the recorder is ready to plot.

This recording system imposes some unusual requirements on the writing system (pen, ink, and paper). For purposes of archival-quality records, neatness, and easy replacement, a fiber-tipped disposable ink pen is used. Although maximum slew speed typically limits this pen, in the ECG recording a second problem, velocity modulation, dominates. This is the tendency for the trace line to thin both in width and in intensity as pen velocity increases. The segmented nature of the data is emphasized by this effect and it is overcome by carefully matching the resistance and capillarity of the pen components. The combination of a carefully designed pen and an ink matched to clay-coated paper produces highly readable ECGs.

A single chip microcomputer controls the recorder. It interfaces to the 4700A controller for data and commands, drives the recorder in an orderly fashion through the servomechanism integrated circuits and the optical shaft encoders and monitors the recorder for error conditions.

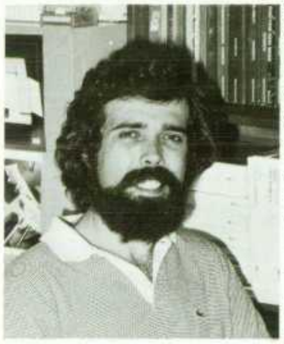
Martin K. Mason

Marty Mason joined HP in 1976, was a development engineer for the 4700A cardiograph and is project leader for pulmonary function development. He is co-author of a paper on a biochemical assay method, and is a co-inventor for three patents related to the 4700A's servo and paper alignment designs. He attended the Massachusetts Institute of Technology where he earned the BS degree in physics (1974) and the MS degree in mechanical engineering (1976). Born in Chicago, Illinois, he now lives in West Newbury, Massachusetts. Marty is married and about to become a new father. He is a member of the Tanglewood Festival Chorus and enjoys restoring old houses and cars. He is currently working on two houses and an antique Jaguar XK120.

Steven J. Koerper

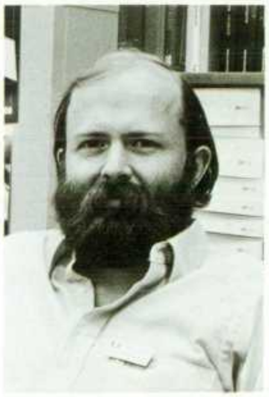
Steve Koerper was born in Milwaukee, Wisconsin and attended the University of Wisconsin at Madison where he received the BSEE degree in 1968 and the MSEE degree in 1969. He joined HP in 1969 and worked on various data communication aspects of HP's ECG Management System. Steve is section manager for the diagnostic cardiology product lines and was the project manager for the 4700A. He lives in Littleton, Massachusetts, is chairman of the Littleton Historical Commission and a church trustee, and coaches Little League and Youth Soccer. Steve is married and has two daughters. His interests include racquet sports, soccer, softball, cross-country skiing, photography, and stained glass. He and his wife live in a seven-level contemporary home that they built.

Steven A. Scampini



Steve Scampini is a native of Bristol, Connecticut. After several years of working on undersea electronics design he joined HP in 1976 and is now a development engineer for the electrocardiography product line. Steve received the BSEE degree in 1972 from Rensselaer Polytechnic Institute, Troy, New York, and the MSEE degree in 1973 from the California Institute of Technology. He lives in Lawrence, Massachusetts and enjoys running and black-and-white photography.

Peter H. Dorward



Peter Dorward came to HP in 1975 and wrote software for the 5600C ECG Management System. He worked on the main control and memory boards for the 4700A and recently became the project manager for cardiography instruments. He attended Dartmouth College, Hanover, New Hampshire, and earned the bachelor of arts degree in engineering sciences (1973) and a master of engineering degree (1975). Peter was born in Lancaster, Pennsylvania, is married, and lives in a 100-year-old farmhouse in Harvard, Massachusetts. He is renovating his home for wood and solar energy heating and does some farming—raising chickens, growing vegetables, and planting fruit trees. He enjoys cross-country and downhill skiing and playing softball.

Acknowledgments

Engineering team members deserving the credit for a great job are Marco Riera who was responsible for the power input module, power supply, recorder electronics, and recorder firmware, Bruce Schurmann, system software design and firmware, Charlie Monroe, printback firmware, Bob Graves, cart and ECG mechanical design, Larry Perletz, who worked on the pen, ink, paper and cable, Pete Rhoads, package and cart industrial design, Greg Vogel, mechanical parts, Ted Minor, package and plastic parts, and Roger Lepine, prototype specialist. Special thanks to HP's Optoelectronics Division for the shaft encoder, to Corvallis Division for the servomechanism IC, and to the Applied Physics Laboratory of HP Laboratories for their inputs, expertise, and support.

SPECIFICATIONS

HP Model 4700A PageWriter Cardiograph

BASIC OPERATING MODES:

Mode	Recording Speed	Sensitivity	Frequency Response	Lead Selection
Auto	Auto 25 mm/s Rhythm Strip 2.5, 5.0, 10, 25, 50, 100 mm/s	Auto 0.5, 1.0, 2.0 cm/mV Rhythm Strip 0.25, 0.5, 1.0, 2.0 cm/mV	0.05-100 Hz or 0.05-40 Hz, selectable	Standard 12 leads plus selectable 1 lead rhythm strip
Manual	25, 50, 100, 200 mm/s	0.25, 0.5, 1.0, 2.0 cm/mV	0.05-100 Hz or 0.05-40 Hz selectable	Any one of 6 lead groups (3 leads each)
Rhythm	2.5, 5.0, 10.0, 12.5, 25, 50 mm/s	0.25, 0.5, 1.0, 2.0 cm/mV	0.05-100 Hz, 0.05-40 Hz, 0.5-100 Hz, 0.5-40 Hz, selectable	Any one lead, switchable during recording

CHART SPEED ACCURACY: ±1% at all speeds (200, 100, 50, 25, 12.5, 10.0, 5.0, 2.5 mm/s).

FREQUENCY RESPONSE: 0.05 to 100-Hz bandwidth (meets AHA recommendations). 40-Hz upper cutoff and 0.5-Hz lower cutoff selectable.

ELECTRODE INPUT IMPEDANCE: Greater than 50 megohms resistance shunted by less than 1400 pF at the patient cable tips.

PATIENT ISOLATION: Less than 10 μA leakage with 120 Vac at patient input.

STANDARDIZATION: 1.0 mV ±2%, 200 ms ±1%.

DEFIBRILLATION PROTECTION: Protected against defibrillator damage from 400 watt-second discharges.

AUXILIARY OUTPUT: 1.0V/mV at 1.0 cm/mV sensitivity. 0.05 to 500 Hz frequency response.

PEN LIFE: Approximately 200 Format 1 AUTO mode ECGs.

COMMON MODE REJECTION: 115 dB or greater in any lead with 51 kilohm in parallel with 0.047 μF electrode impedance imbalance and up to ±300 mV dc offset in any lead.

INPUT BIAS CURRENT: Less than 100 nanoamperes per lead.

DC OFFSET SENSITIVITY: ±300 mV dc offset at patient input results in less than 5% gain change.

CROSSTALK: Greater than 40 dB down with a full-scale signal on the other two channels (0.05 Hz to 100 Hz).

ECG MEMORY:
Complete COPY of AUTO or MANUAL records.
Up to 40 lead seconds of SAVED data during RHYTHM.

LEAD GROUPS:
(1) I, II, III (2) aVR, aVL, aVF
(3) V1, V2, V3 (4) V4, V5, V6
(5) Special leads nominally set to II, aVF, V5
(6) Optional leads

SAFETY: Meets applicable IEC, VDE, UL, CSA, AHA, FDA specifications.

LINE POWER (ac Module): 100/120/220/240V, 47-66 Hz, 75 VA max.

ENVIRONMENTAL OPERATING CONDITIONS: 0 to 55°C, 0 to 95% relative humidity, sea level to 15,000 feet altitude.

SIZE (HWD): Model 4700A, 11.2 × 39.4 × 42.2 cm.
Model 4720A Cart, 90.2 × 50.8 × 83.8 cm.

WEIGHT: Model 4700A, 8.5 kg without cables. Model 4720A Cart, 11.7 kg.

PRICE IN U.S.A.: 4700A, $4950.
4720A, $375.

MANUFACTURING DIVISION: ANDOVER DIVISION
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Andover, Massachusetts 01810 U.S.A.

Hewlett-Packard Company, 3000 Hanover Street, Palo Alto, California 94304

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