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# HEWLETT-PACKARD JOURNAL

# HEWLETT·PACKARD JOURNAL

Technical Information from the Laboratories of Hewlett-Packard Company


## Contents:

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## In this Issue:

How do you replace an act that's been playing for twenty years and is still drawing plenty of customers? Engineers at HP's Stanford Park Division had to find the answer when they set out to design replacements for HP's long-lived line of klystron signal generators. These generators are much prized by customers who need tunable sources of pure stable microwave frequencies. In each generator is a klystron oscillator tube, its frequency of oscillation determined by a mechanically tuned microwave cavity (a metal-enclosed space of controlled size and shape). The cavity-klystron combination is hard to beat for spectral purity, but it makes for a big, unwieldy package, and just about any twenty-year-old design can be improved by applying the latest technology. The engineers kept the cavity tuning, replaced the klystrons with transistors, added a microprocessor, applied up-to-date circuit design techniques and some novel ideas, implemented many critical circuits as state-of-the-art microcircuits, and gave us the new 8683A/B and 8684A/B Microwave Signal Generators. The project took a long time because it wasn't easy to match that klystron spectral purity, but the new generators do match it and surpass the old generators in every other performance area. You'll find an overview of the new generators on page 16, a description of the cavity-tuned oscillators on page 20, and other design articles on pages 26 and 30. Our cover photograph this month shows the disassembled cavity and tuning mechanism in front of the 8684B Signal Generator. The cavity mechanism lives behind the knob on the left side of the front panel.

Pages 3 through 15 of this issue complete our coverage of the 2680 Laser Printing System. Last month's issue was entirely devoted to this versatile, cost-effective computer output printer. This month you can read about the optical system that guides the laser beam on its path from the laser to the photoconductive drum, and about the machine control system, the microprocessor-based electronic subsystem that monitors and controls the printer.

In this year's January issue we enclosed a reader opinion questionnaire. Our computer has now digested the returns and is beginning to give us data that will help shape the future of the Hewlett-Packard Journal. Worldwide, about 4% of our readers returned the questionnaire. Many enclosed notes and letters. We were pleased to find that 49% of our readers have been with us more than five years and 53% file the Journal for reference. To those who shared their opinions with us, our sincere thanks.

*-R. P. Dolan*

# Optical System Design for the Laser Printing System

*Here are the details of the optical system of the 2680 Laser Printing System described in these pages last month.*

**by John R. Lewis and Laurence M. Hubby, Jr.**

THE OPTICAL SYSTEM of the 2680 Laser Printing System is designed to provide the highest resolution and printing speed possible consistent with reasonable economy of production, the data rate capability of the digital electronics, and the properties of the electrophotographic process. A variety of factors influenced the choice of each component and the configuration chosen for each portion of the design.

In the optical system, light from a laser source is shaped into a spot of the desired diameter at the photoconductor drum by the scan lens. Action of the scanner produces a line scan across the drum, forming the horizontal portion of a high-resolution raster scan. The rotation of the drum provides the vertical scan. A stream of information is impressed upon the light beam by the modulator in response to commands from the character processor.

The scanning system is required to produce a spot of accurate size that yields the required developed dot diameter. The length of the scan line produced must be sufficient to cover the desired copy size (European A4 paper, 210×297 mm), and thus a number of resolvable spots equal to the ratio of these two quantities is required. Laser power should be sufficient to allow copy to be produced as fast as permitted by either the electrophotographic process or the rate at which data can be written, whichever is more restrictive, and the capabilities of the scanner and modulator must be consistent with this speed.

## Laser and Process Characteristics

A helium-neon laser was chosen for several reasons. First, the demonstrated maintenance-free life of hard-sealed helium-neon lasers (20,000 hours) is three to ten times longer than that of any of the other candidates, while its initial cost is of the order of ten times lower. Second, the size and power consumption of these units are modest, particularly compared to devices such as ion lasers. Third, the wavefront quality produced by the device is excellent, and fourth, the photoconductor sensitivity at the HeNe emission wavelength (633 nm) is good.

The dot placement resolution used in the 2680A is 141 μm, corresponding to an optical dot size of about 125 μm, and the exposure required is about 1.5 microjoules per square centimetre, corresponding to an optical energy required for each dot of $1.85 \times 10^{-4}$ μJ. A five-milliwatt laser is used, allowing dots to be written at a rate given by:

$$\text{Rate} = (5\times10^{3}\ \mu\text{J/s})/(1.85\times10^{-4}\ \mu\text{J/dot}) = 2.71\times10^{7}\ \text{dots/s}$$

The actual writing rate cannot be this high because the optical system has an overall transmission of about 35%, and a safety margin of roughly another factor of 1.5 must be allowed to account for the decrease in the laser's power over its useful life. The required dot rate is thus something less than $6\times10^{6}$ dots/second, corresponding to a data rate of about 0.75 megabytes/second. The five-milliwatt laser is quite adequate for these numbers. This is fortunate because the price and physical size of helium-neon lasers increase dramatically as the output power exceeds five milliwatts.

The helium-neon laser requires an external modulator for such data rates, and devices operating on two different principles were given consideration: acoustooptic and electrooptic. The data rates required are a problem for neither. However, the acoustooptic modulator is free from thermal drift effects which cause the electrooptic device to require periodic readjustment, is more compact and cheaper, will work with unpolarized light without causing additional loss, and does not require high-voltage components in its driver. It was therefore the obvious choice.

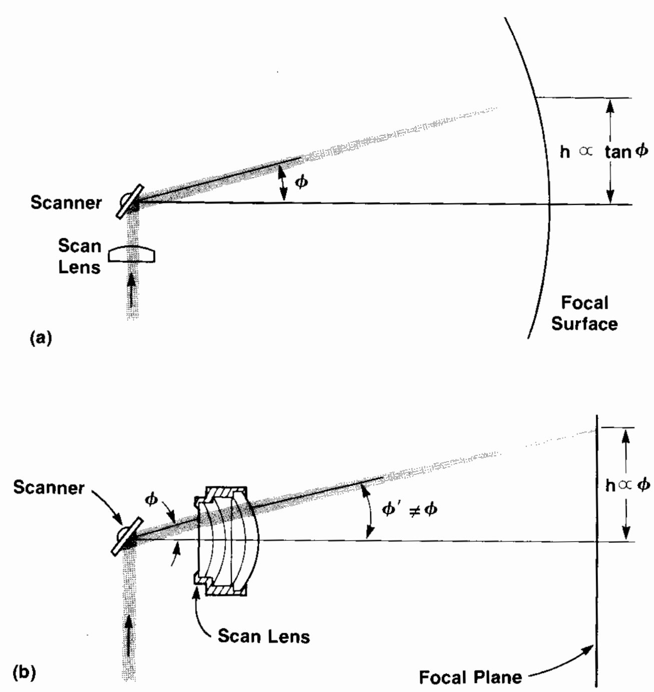



**Fig. 1.** *(a) Postobjective scanning. (b) Preobjective scanning. The 2680A Laser Printer uses (a).*

## Scanning Method

The scanning system consists of two major parts, the scan objective lens and the scanner. The order in which the beam encounters these two components as it progresses toward the final image plane forms the basis for the usual classification of scanning systems as either postobjective or preobjective. Postobjective scanning is shown in Fig. 1a, and is attractive because only a very simple scan lens is required (frequently just a single element). The arrangement has the disadvantage, however, of producing a curved focal surface. Preobjective scanning, shown in Fig. 1b, requires a much more complex scan lens, but this complexity can then be exploited to produce not only a flat focal plane, but one corrected for angular distortions as well. The major factors that determine which configuration must be used are the system resolution and overall size constraints. As shown in Fig. 2a, a laser beam near focus remains nearly constant in diameter for a finite distance, called the depth of field, and this distance increases as the square of the f-number of the lens that produces the focus. Since the size of the focused spot also depends upon this same quantity, the lens f-number and hence the depth of field are determined by resolution requirements and the wavelength of the laser light. If the resulting depth of field is large enough and/or the scanning system can be located sufficiently far from the scan plane, a curved focal surface can be tolerated, as shown in Fig. 2b, and postobjective scanning may be used. In the case of the 2680A, the required spot size is 125 $\mu$m and the laser wavelength is 0.6328 $\mu$m. Thus:

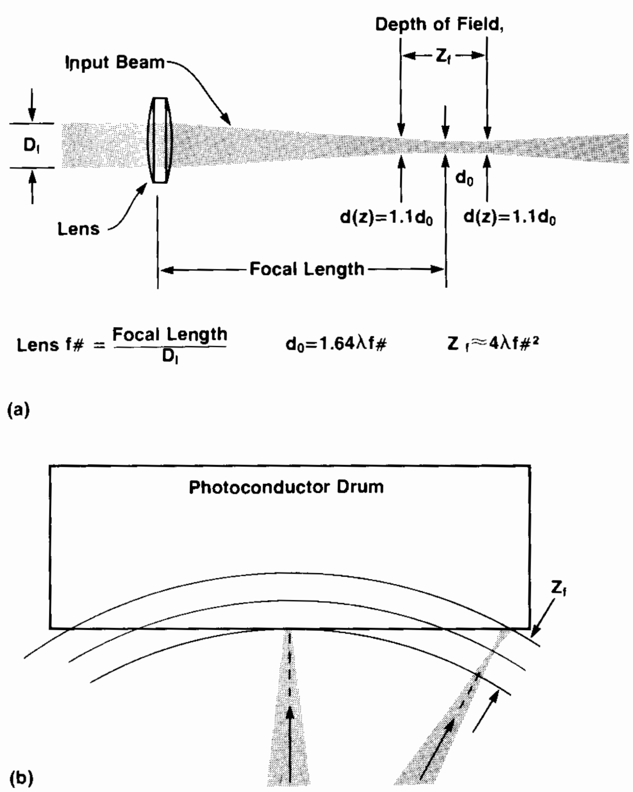



**Fig. 2.** *If the depth of field of the focused laser beam is sufficient, a curved focal surface can be tolerated.*

$$\text{scan lens f-number} = (125\ \mu\text{m})/(1.64\times 0.6328\ \mu\text{m}) = 120$$

Therefore:

$$\text{depth of field} \approx (4\times 0.6328\ \mu\text{m})\times 120^2 \approx 36.4\ \text{mm}$$

Using the geometry of Fig. 2b and allowing a factor of roughly two for tolerance buildup in the remainder of the system, we could then place the scanning system about 850 mm from the photoconductor drum, corresponding to a scan half-angle of about 10 degrees. The difference between x and tan(x) at this angle is only is only about 1%, and thus the angular distortion shown in Fig. 1a would be so small as to need no correction or only very slight correction. These are reasonable numbers, and such a basic layout was chosen for the 2680A scanning system.

The specifications the scanner must meet have by now been fairly well defined, either directly or indirectly. The scanner must resolve a number of spots given by:

$$\text{number of spots} = \text{length of scan line} \div \text{spot size} = (289\ \text{mm})/(141\ \times 10^{-3}\ \text{mm}) = 2048\ \text{spots}$$

within the aforementioned scan angle of about 20 degrees. The lines must be scanned at a rate that corresponds to a maximum dot rate of about $6\times 10^6$ dots/s. Also, the scanning system has a finite duty cycle (fraction of time spent printing). Assuming a duty cycle of 46%, the line scan rate is approximately:

$$\text{line scan rate} = (0.46)(6\times 10^6\ \text{dots/s})/(2048\ \text{dots/line}) = 1350\ \text{lines/s}$$

The performance of scanners based upon rotating polygonal mirrors, single mirrors attached to galvanometers, acoustooptic interactions, and the electrooptic effect in certain crystals were considered in light of the above requirements, and it quickly became obvious that only the first of these devices could achieve both the required resolution and scan rate comfortably at a reasonable cost. The electrooptic devices are not capable of enough spots. Acoustooptic deflectors have been reported with up to 10,000-spot capability, but these devices are complex and expensive. Mirrored galvanometers are capable of enough spots, but can only achieve the required scan rate in resonant systems. This would require the scan velocity to vary sinusoidally, resulting in line-linearity and exposure-level variations that would be unacceptable unless the field were very substantially overscanned. Since such overscanning would require an unacceptably low duty cycle, galvanometers were eliminated from consideration.

## Wobble Correction

Rotating polygon scanners are not without their problems, however. Primary among them is pyramid error in the orientation of the individual facets of the polygon. This type of defect causes the light reflected from successive facets to arrive at the scan plane at different locations in the direction perpendicular to that of the scan. Since successive facets correspond to successive scan lines on the drum,

(continued on page 6)

# Laser Printer Optics Control and Diagnostic Circuit

by Gary L. Holland

Within the 2680A Laser Printer's optics casting is the optics control and diagnostic circuit, which performs the following functions:

- It drives the acoustooptic modulator with variable RF power to allow analog modulation of the laser beam as well as on/off control.
- It monitors the RF power driving the acoustooptic modulator.
- It monitors the laser power deflected onto the drum.
- It provides a synchronization signal to align data correctly for successive scans across the drum.

### Acoustooptic Modulator Driver

This section of the circuit modulates an 80-MHz signal to the acoustooptic modulator (Fig. 1). The machine control system (MCS) processor sets the laser power through a digital-to-analog converter (DAC). Intensity setting 00 corresponds to low RF power into the laser modulator and hence low laser power. Increasing intensity values result in increasing RF power into the modulator. This results in increased optical power up to the point when the laser modulator saturates, and then optical power begins to fall off. This saturation point varies from modulator to modulator. The on/off signal VIDEO enables the RF power when high and disables it when low. The 80-MHz oscillator consists of an ECL gate, a crystal, and tank and loading circuits. The signal from this oscillator is modulated with a diode modulator. The amount of 80-MHz signal going through the modulator is roughly proportional to the current drawn from the modulator by the programmable current source, which is set by the machine control processor. When VIDEO is low, a switchable current source provides current to the RF modulator and the programmable current source, and the RF modulator is reverse-biased so that no signal goes through the modulator. When VIDEO is high, the switchable current source is turned off, and the programmable current source then sinks current out of the RF modulator, turning it on and allowing a preset amount of 80-MHz power to go into the acoustooptic modulator.

The output amplifier that drives the acoustooptic modulator is a hybrid amplifier. Its output is monitored by a peak detector. A fraction of the peak value is buffered and sent to the machine control system to indicate to the MCS the magnitude of the RF power.

### Beam Detection and Laser Monitoring

The beam-detect section (Fig. 2) monitors the first-order power and detects when the beam sweeps across the beam-detect diode. The first-order power is the portion of the laser power deflected through the acoustooptic modulator when RF power is applied to it by the modulator driver section. The first-order power is monitored only as the beam sweeps past the beam-detect diode. An amplifier buffers the signal and a peak detector produces a voltage proportional to the power into the beam-detect diode. The peak voltage is called FIRST-ORDER POWER. This signal is divided by 2 and compared with the buffered output from the beam-detect diode. When this output passes through its half-peak points, a comparator switches and the driver sends this switched signal back to the data control system. This signal is called BEAM DETECT and is the horizontal sync signal.

The machine control processor uses the FIRST-ORDER POWER signal to monitor the amount of laser power going onto the drum. The MCS can then alter this power by altering the amount of RF power sent to the acoustooptic modulator as explained above.

### Diagnostics

The optics diagnostics are executed in the print mode once per drum revolution when the drum seam is in front of the modulated beam. The two parameters that are measured with the analog-to-digital converter and used for fault detection are FIRST-ORDER POWER (FOP) and RF driver output power (MOD PWR OUT).

To prevent possible safety hazards, the RF output power going into the acoustooptic modulator is monitored with the RF driver turned off. This is monitored both in and out of the print mode. If any RF power is detected when the laser should be off, the laser power supply is disabled, the ac contactor is opened, and the +28-volt supply is disabled.

The following is a list of all the possible optics failures in the order in which they are detected: 1) RF driver stuck on, 2) RF driver failure, 3) scanner failure, 4) beam detect failure, 5) scanner start failure. Some of the failures require the electrostatic loop potentials to be out of range before a failure is flagged. If the loop is limited, a warning message is displayed. In the service command mode the warnings are flagged whether the loop is limited or not. This applies to RF driver failures and beam-detect failures.

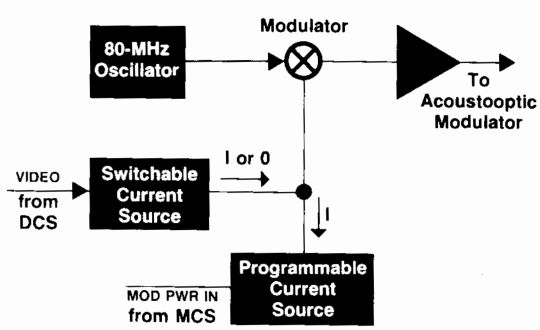



**Fig. 1.** *Acoustooptic modulator driver.*

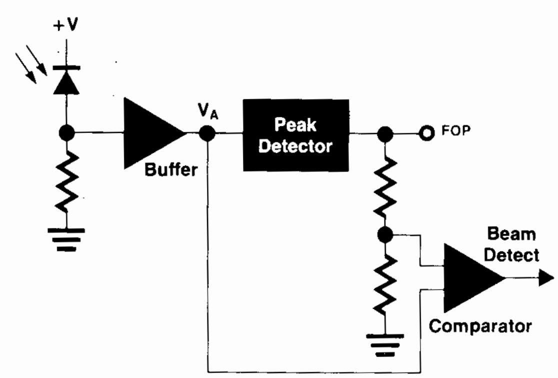



**Fig. 2** *Beam detection circuit.*

printed copy produced with a scanner exhibiting this problem contains periodic errors in the vertical placement of the dots that form the characters, a condition we call wobble. Controlling wobble by decreasing the residual pyramid error in the polygon during manufacture can be an expensive proposition, since the angular accuracy required is of the order of one second of arc. Fortunately, an optical solution to the wobble problem exists, as shown in Fig. 3. If the beam is brought to a focus in the direction perpendicular to that of the scan at the face of the polygon and then refocused to its original form after deflection, the vertical position of the beam at the scan plane will be independent of pyramid error in the polygon, and hence the final print will exhibit no wobble. The lenses involved must, of course, be sufficiently well corrected to maintain the required final spot size as well as the action just described over the range of motion of the scanner. This is not a trivial requirement for the lens that follows the scanner, particularly if preobjective scanning is used and this lens must form the final spot in the scan direction as well. As shown in Fig. 4, the natural form for this lens is toroidal, essentially that of a cylinder lens bent into an arc so as to be equidistant from the polygon face at all points in the scan. Such lenses can be built, either with conventional glassworking or plastic injection molding techniques. However, the accuracy necessary to achieve good performance is difficult and therefore expensive to maintain.

A viable solution from a cost standpoint would be to use a simple cylinder lens following the scanner, and if the scan angle could be held to small enough values, this would be acceptable optically as well. Unfortunately, the scan half-angle would have to be reduced to less than three degrees, which would increase both the scanner-to-scan-plane distance and the polygon size to unreasonable values. The solution developed for use in the 2680A is shown in Fig. 5. Two additional lenses, which use only spherical surfaces and form essentially a unity-magnification Galilean telescope, surround the simple cylinder lens and create a region in which the scan is angularly compressed. An alternative description is that the apparent source of the light that passes through the cylinder lens is now a distant image of the active polygon facet produced by the first additional lens. The second spherical lens then reimages the scanner to the original apparent distance from the scan plane. The result is that the maximum angle at which the beam must pass through the cylinder lens is sufficiently reduced that

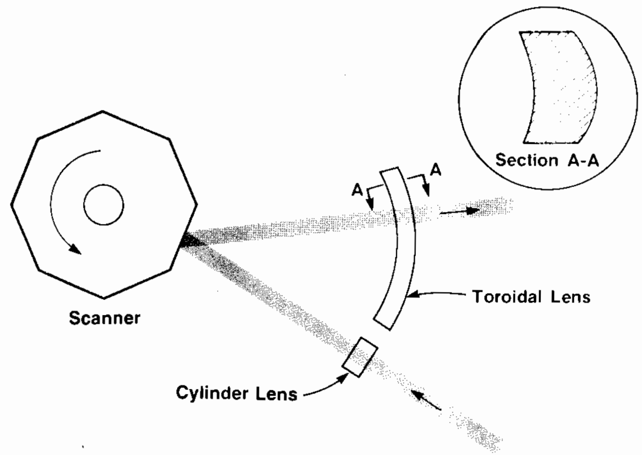


**Fig. 4.** *Toroidal lens form for wobble correction.*

satisfactory optical performance is maintained over the entire length of the scan, and yet the system is simpler and less costly than it would be if preobjective scanning were used. The system has the additional benefit of naturally tending to flatten the focal surface, since the beam passes through a greater thickness of glass at the extremes of the scan than it does in the center. The final design of the 2680A scanning system produces an almost completely flat focal surface, making the entire depth of field available to compensate for tolerance buildup elsewhere in the system.

### 2680A Optical System

The complete 2680A optical system, shown in Fig. 6, contains a few other components whose functions are perhaps best explained by following the beam through the system. Light leaving the laser first encounters a lens which produces a spot of appropriate size in the modulator crystal to obtain the optimum compromise between speed and efficiency in this device. The modulator, in effect, turns the beam on by deflecting it through a negative lens whose purpose is to expand the beam in a reasonable distance to the diameter required by the combination of the scan lens f-number and working distance. The beam next encounters the single-element scan lens, which causes it to converge toward a focus at roughly the drum location. A short distance farther along the path is the first wobble-correcting cylinder lens, which focuses the beam to a line focus in the

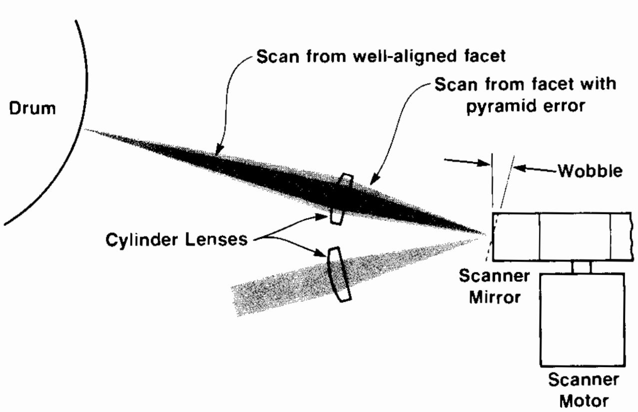


**Fig. 3.** *Wobble correction.*

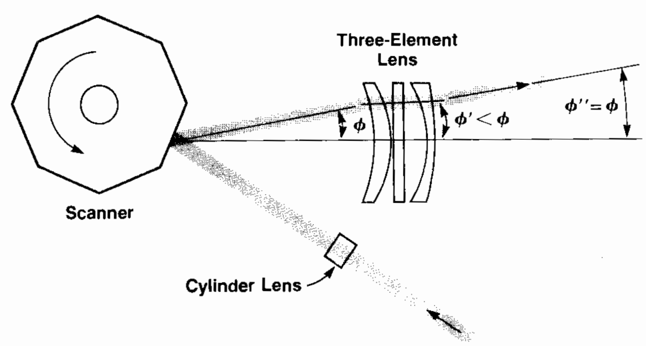


**Fig. 5.** *The 2680A Laser Printer uses a three-element lens for wobble correction.*

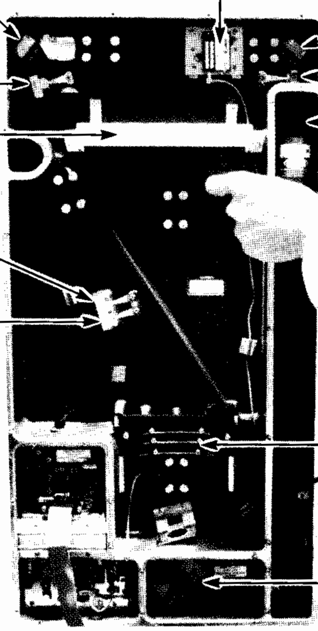



**Fig. 6.** *2680A Laser Printer optical system.*

plane of the page on the active facet of the polygon. The polygon has 18 sides, giving a total scan angle of 40 degrees, about half of which is used for writing. The remainder allows time for the apexes of the polygon to pass through the beam and a beginning-of-scan sync mark to be detected. The polygon measures 60 mm between opposite faces and turns at 4500 r/min. After reflecting from the polygon, the beam passes through the set of three lenses described above—spherical, cylindrical, and spherical—which complete the wobble correction. This group is placed a distance from the polygon that yields a slightly elliptical final spot whose minor axis is aligned with the direction of scan. This helps obtain a round printed dot because it partially compensates for the blurring effect of the motion of the beam during exposure. After the final lens group, the beam is reflected through 90 degrees by a long turning mirror and passed through a window out of the optics assembly toward the photoconductor drum. A mirror intercepts the beam shortly before it reaches the beginning of each scan line and reflects it to a photodetector which generates the scan sync signal.

### Mechanical Design Considerations

The optics assembly is designed to be a field-replaceable module with no adjustments required. This means that the alignment between the optics assembly and the rest of the printing process is critical and must be as free as possible from product assembly errors or tolerance buildup. The mounting details for the optics module are on the process module, and the resulting assembly is suspended from the main machine frame in such a way as to be relatively independent of gross frame errors.

The requirements of optical alignment between modules do impose special requirements on the machine structure. If special installation leveling and adjustments are to be avoided, the frame must be stiff enough to hold the required alignment geometry over the full range of weight distribution between casters or levelers. This requirement was met with a welded box tube base and a welded steel channel frame. This design holds the required optical alignments even if one of the front casters is completely off the ground. This means that no special installation alignment is required, although it is recommended that the levelers be nearly evenly loaded for best results.

The process module is a very dirty environment with loose, statically charged, black toner dust and paper dust, and blowing, rubbing, and throwing mechanisms to distribute it all over. To protect the optics from this environment, and to protect the operator and service person from the laser beam, a conduit contains the output beam between the optics module and the point in the printing process where the light is used. A window on the optics module keeps air flows and contaminants from the interior of the module, and a small blower draws in filtered air to keep the conduit at a positive pressure with respect to the sources of contamination. This system also reduces contamination on other critical process components.

### Layout and Folding

The long-focal-length lenses used in the optics result in a path length of 2.3 metres from the end of the laser to the spot on the drum. The scanning mirror and two other mirrors fold this optical path into a reasonable-size package 366 by 712 by 72 mm. Vertical placement of the package along one side of the machine uses the interior space of the machine efficiently.

Since the system uses long focal-length lenses, it is relatively tolerant of errors in element placement along the optic axis. As a result, it was possible to eliminate all lens adjustments in the direction of the optic axis. This approach requires more care in lens fabrication and location, but results in fewer parts, more reliability, faster assembly, and simpler alignment. Each lens is located by fixed details in a machined housing. Only the folding mirrors and the modulator Bragg angle* are adjustable.

The long focal length of the lenses and the resulting long path are disadvantages in that they increase the sensitivity of the assembly to torsional deflections. A sand casting was chosen to form the base of the module because of its relative stability and stiffness. Even with a rigid casting as the reference for the assembly, it is important to avoid any torsional loading on the module. As a result, the attachment to the rest of the machine uses just three mounts so that distortions of the rest of the machine tend only to mislocate the housing and not to twist it.

### Lens and Laser Mounts

The first four lenses and the laser are held against the sides and bottoms of machined slots in the casting with simple leaf springs (Fig. 7). These lenses are thick and have well specified mechanical-to-optical tolerances so they can

*Bragg angle is a characteristic angle at which light rays reflect from planes of atoms in a crystal.

# A Synchronous Mirror-Motor Drive for the Laser Printer

**by Gary L. Holland**

In the optics assembly of the HP 2680A Laser Printer, a motor spins the polygon mirror to sweep the laser beam across the page. The scanner motor is driven at a constant angular velocity of 75 revolutions per second.

The armature of the motor is the stator and the field is supplied by a permanent magnet in the rotor. By sequentially energizing the coils in order of phase number, a rotating magnetic field is created in the stator. Under normal operating conditions, the magnet (the rotor) follows this magnetic field, lagging slightly behind it.

Two Hall-effect devices are an integral part of the motor. These give sinusoidal output voltages as the rotor turns, and are phased such that their waveforms are 90 degrees apart. Referring to Fig. 1, the scanner drive servo block diagram, the analog-to-TTL converters give logical one outputs, +5V, whenever the output of their corresponding Hall generators are in the positive half cycle. Therefore, a positive zero crossing results in a positive TTL edge, and a negative zero crossing results in a negative TTL edge. Under slowly rotating conditions, when one coil at a time is energized, a negative edge on Hall generator 1 (HG1) occurs when phase 1 is energized, a negative edge on HG2 for phase 2, a positive edge on HG1 for phase 3, and a positive edge on HG2 for phase 4. These edge definitions assume counterclockwise rotation. Fig. 2 shows these time relationships. The zero phase lag waveform for the Hall generators is the slowly rotating condition described above, and the waveforms below those show more typical running conditions, with the rotor lagging somewhat behind the stator field.

Notice that the current waveforms through the windings labeled phase 1 through phase 4 are always in the same place in relation to the counter values listed at the top of Fig. 2. This is because the counter, located in the middle of Fig. 1, is the device that defines where the current waveforms are in the cycle. The output of the counter addresses the ROMs, which output digital sine and cosine functions. This digital information is then converted to analog waveforms, which are processed to define currents through the coils of the motor as shown. This is the basic drive system for the motor.

### Jitter Compensation

The circuitry already described is enough to drive the scanner motor. A problem that remains is a low-frequency jitter which takes about five minutes to damp out after startup. To damp this out faster, a compensation circuit uses phase information to move the poles of the system away from the imaginary axis of the s-plane. This scheme uses a phase comparator to give a signal inversely proportional to the phase lag of the rotor. This signal is ac-coupled into the compensator and conditioned. It is then added to a dc level which sets the peak values of the scanner drive signals. As the phase lag varies, the compensation signal acts to keep the lag constant.

### Speed-Detection Circuitry

Included in the speed-detection section are a counter, a latch, and gates to interrupt the machine control processor once every sixteen revolutions of the scanner motor. With this information the processor can tell if the scanner is up to speed or if there is a failure in the circuitry that drives this motor.

Under normal conditions, the 2.4-kHz clock is the input to the counter's clock input. The counter outputs cycle though the ROM addresses, and the ROM data defines sine and cosine waves which cycle at 75 Hz. This data is converted to analog waveforms which are multiplied by the output of a compensator and centered about zero volts. The splitter/current-driver circuit rectifies the cosine wave and drives phase 1 with current proportional to the resulting waveform. Phase 2 is similarly derived from the sine wave, phase 3 from the inverse of the cosine wave, and phase 4 from the inverse of the sine wave.

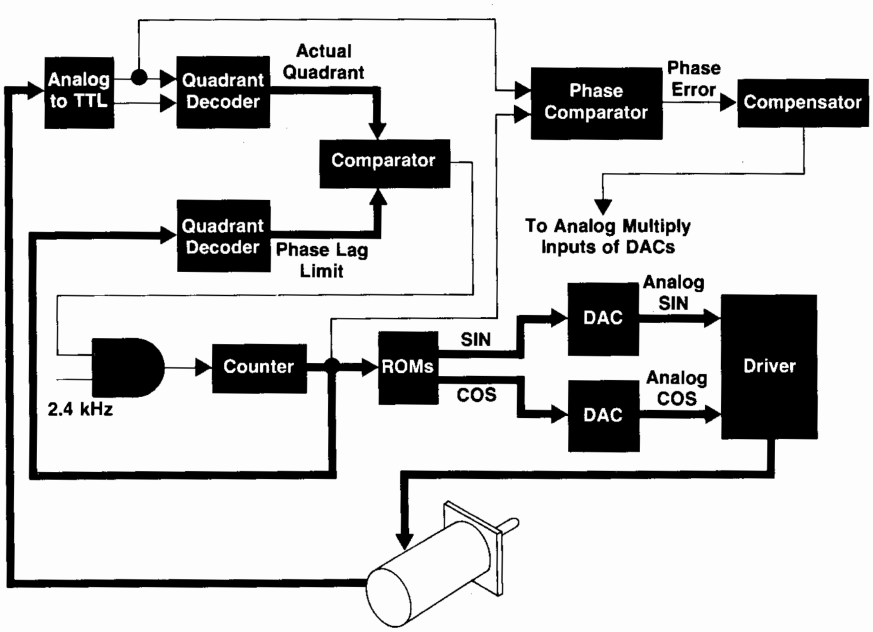



**Fig. 1.** *Scanner drive servo block diagram.*

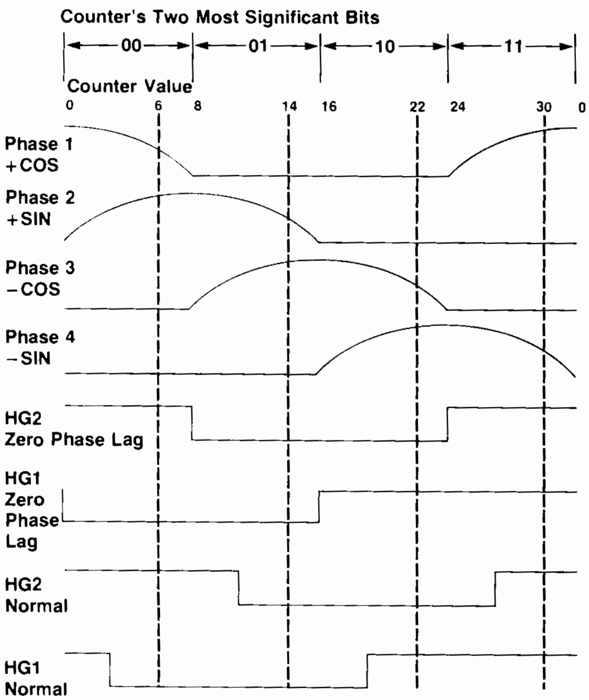



**Fig. 2.** *Scanner drive timing relationships.*

### Starting the Motor

One cannot simply create a magnetic field rotating at 75 revolutions per second in the stator and have the rotor follow along, because the rotor cannot start to move this fast. Starting is accomplished by beginning to cycle the magnetic field at 75 Hz, but stopping the waveform to allow the rotor to catch up four times per revolution. The four counts on which the waveform may be stopped are 6, 14, 22, and 30. These are indicated in Fig. 2. If the counter is up to six and HG1 is still 1, there is a phase lag of nearly 90 degrees between the stator field and the rotor field. In this case, the clock is disabled until it falls to 0 and is then enabled again. If HG2 is still 1 when count 14 comes along, the clock is disabled until it falls to 0; if HG1 is still 0 when count 22 appears, the wave is stopped until it becomes 1; and if HG2 is still 0 when count 30 is encountered, the clock is disabled until it becomes 1.

**Gary L. Holland**

Gary Holland was born in Chewelah, Washington and received his BSEE and MSEE degrees from Washington State University in 1976 and 1980. He's been a development engineer and production engineer with HP's Boise Division since 1977. He is listed as inventor or co-inventor on five pending patents related to the 2680A Laser Printer. Gary has taught circuit theory at Boise State University. His interests include amateur radio, woodworking, music, photography, and hiking. He's married, has three children, and lives in Boise.

be referenced to the side surfaces instead of the optical faces.

The last three lenses are held against machined details in the casting as well, but since these lenses are optically thin, they are held by their optical faces. Torsion springs provide pressure in the direction of the optic axis and allow a large tolerance in spring fabrication. A carrier holds the torsion springs for all three lenses, along with screws to cage the lenses. These screws are adjusted during assembly to eliminate clearance but not press on the lenses. The mount slides on a track machined into the casting to simplify assembly (Fig. 8).

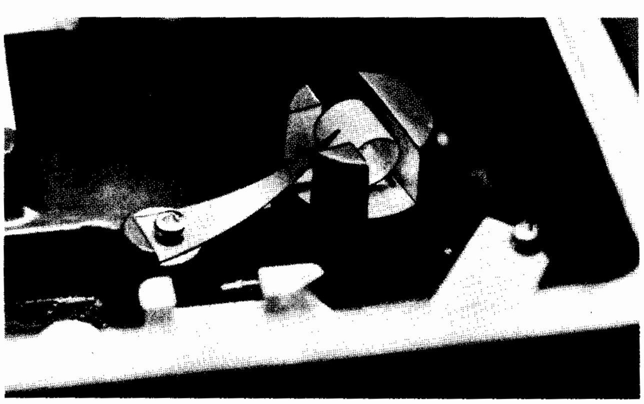


**Fig. 7.** *Leaf springs hold the thicker lenses and the laser in machined slots.*

### Scanner Drive

In addition to the optical parameters of the scanner, the physical dimensions of the scanning polygon affect the output print quality. The distance from the facet center to the rotational axis must be the same from facet to facet. Any variation in the facet-to-axis dimension shows up as a change in the velocity of the scan and causes printed lines to have a jagged edge on the side away from the synchronization detector.

The polygonal mirror is carefully machined of aluminum so the facet-to-axis distance can be precisely specified, and the mounting detail on the drive motor is ground as the motor is rotating. These methods eliminate a multitude of costly tolerances.

### Mirror Mounts

The folding mirrors in the system are adjustable in two axes to allow for some correction of component errors. The first folding mirror aims the input laser beam through the modulator and compensates for errors in the first lens and lens mount. The modulator is adjustable only in the very critical Bragg angle. The adjustments of the second folding mirror further correct the aim and location of the beam through the rest of the system.

An auxiliary mirror is used to send a portion of the beam to a synchronization detector. This mirror is adjustable to allow precise setting of the location of the scan at the drum with respect to the external mounting details of the housing. The exit mirror is supported on one fixed and two adjustable points so that the tilt of the exit beam may be

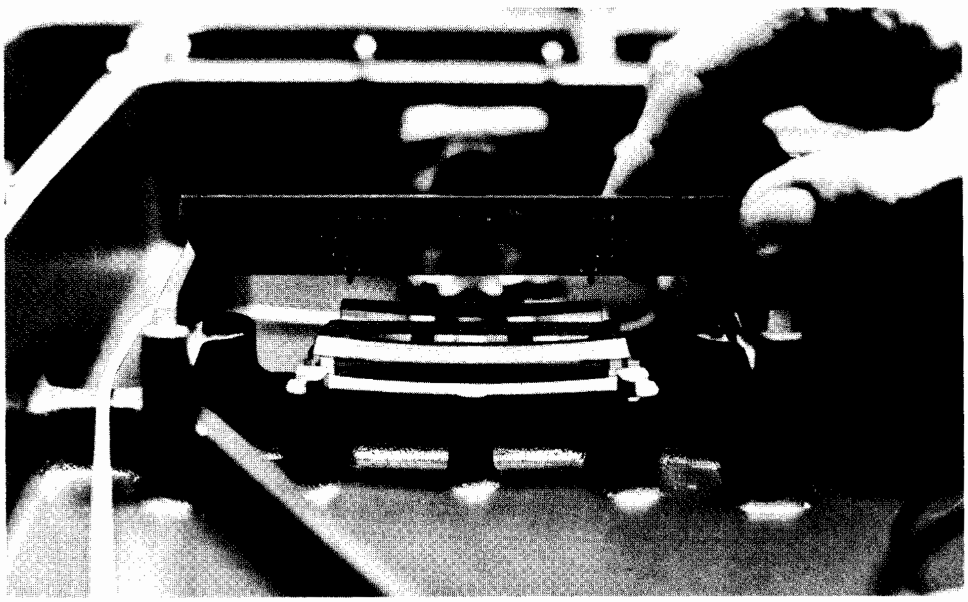


**Fig. 8.** *Torsion springs hold the thinner lenses. The springs are above the plate being held up in this photograph. When the plate is in position, the fingers projecting through the plate press the lenses forward (out of the page) against the posts that can be seen in the picture. The torsion springs can be seen from above in Fig. 6.*

adjusted in two directions. Thus the position of the beam at the writing surface is held precisely even in the presence of imperfect optical elements.

## Manufacturing and Testing

Since the assembly of the optics module does not allow for adjustment of the lens elements, the mechanical dimensions of the lenses are controlled tightly. This increases the lens costs only slightly and saves a great deal in the cost of mounts and individual element alignment. Each lens is carefully checked for mechanical centering, tilt, and wedge.

A more difficult task is the control of the manufactured dimensions of the housing. This single sand casting is machined with a computer-controlled milling machine so that the large number of tightly controlled dimensions may be reproduced consistently. The number of surfaces and the tolerance levels involved required that even the prototype housings be fabricated on a numerically controlled mill.

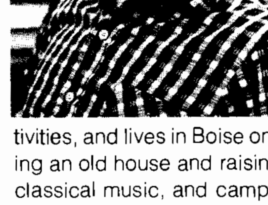
The tolerances required to produce the machined housing are beyond standard manufacturing practice, so a combination of tooling, manufacturing, and inspection improvements were made for this part.

A special operation before the main machining of the part is done to establish a flat, stress-free reference surface. A special setup procedure cuts nonfunctional details on the housing so that the tools may be adjusted according to their actual machining characteristics before cutting important details. This ensures that even the first parts in short manufacturing runs are usable. Each part is monitored after fabrication to return information to the machine operator about how each individual tool is cutting so that cutters may be adjusted or replaced before they produce parts that are out of specification.

**Laurence M. Hubby, Jr.**

Larry Hubby is a project manager with HP Laboratories. Since 1968, when he joined HP, he has worked on laser interferometers, holography, acoustically tuned optical filters, the 2680A Laser Printer, and optical memories. He's co-author of a paper on optical material properties, an inventor on three optical device patents, and a member of the Optical Society of America. He has taught optics and computer programming. A native of Waco, Texas, he received his BS degree from Stanford University in 1967 and his MS in physics from the University of California at Los Angeles in 1968. His interests include good food and wine, building and rebuilding "interesting" vehicles, and the visual arts. He's married, has one child, and lives in San Francisco.

**John R. Lewis**



John Lewis worked on the optics assembly, the frame, the electrophotographic module, and the densitometer of the 2680A Laser Printer. A native of Provo, Utah, he received his BS degree in engineering and applied sciences from California Institute of Technology in 1973 and his MS in mechanical engineering from Stanford University in 1975. With HP since 1974, he worked on solid-state display devices before joining the laser printer project. John is a registered professional engineer in the State of Idaho. He is married, has four children, is active in church activities, and lives in Boise on a one-acre mini-farm where he's restoring an old house and raising animals. He enjoys home computers, classical music, and camping.

### CORRECTION

In our June 1982 issue on the 2680 Laser Printing System, Fig. 3 on page 7 shows the laser printer's photoconductive drum rotating the wrong way. The arrow showing drum rotation should point the other way.

# Laser Printer Machine Control System

*One of two electronic subsystems within the 2680A Laser Page Printer, the MCS monitors and controls the printing process. Its companion subsystem, the data control system or DCS, was described last month.*

**by James D. Crumly and Von L. Hansen**

THE PRINTING MECHANISM of the HP Model 2680 Laser Printing System is monitored and controlled by a microprocessor-based system called the machine control system (MCS). The MCS controls the printing process, paper movement, the operator interface, the electrophotographic process, diagnostics, and most other machine functions. Fig. 1 is a block diagram of the MCS.

The MCS uses an HP-designed 16-bit microprocessor called the MC5.[1] This processor executes a machine control program residing in 32K words of UV-EPROM (ultraviolet-light-erasable programmable read-only memory). There is a 4K-word static RAM (random-access memory) of which 1K is nonvolatile. The nonvolatile RAM contains powerfail information and settable constants for process control. The machine control processor interfaces with over 150 different control devices by means of an I/O bus. Each device resides at a unique I/O address and can be accessed by the microprocessor.

## Operating System

The MCS uses a real-time, multitasking operating system to coordinate the control programs. It became apparent at the start of the project that an operating system was necessary because of the complexity of the control required. The control firmware is divided into independent control modules called tasks. The MCS consists of over 100 tasks controlling the operator interface, paper movement, printing, and diagnostics. These independent tasks execute in apparent parallelism, sharing the single MC5 processor. Using a multiplexing scheme, each task executes for a short period of time in a priority queuing structure.

The operating system handles all task-related bookkeeping and coordinates all tasks in the system, determining when a task executes. All tasks exist in one of four states: active, ready, waiting, and dormant. A task currently executing is in the active state. When an active task finishes its work it enters either a dormant state or a wait state. A task entering the waiting state suspends execution temporarily with a request to be awakened after a specified time delay. When the current active task finishes execution the highest-priority ready task becomes the next active task.

Tasks communicate with the operating system by function calls. These calls provided the means for tasks to change from one state to another. The SUSPEND function is used by an active task when it reaches a point where it must wait for an external event. The operating system then puts

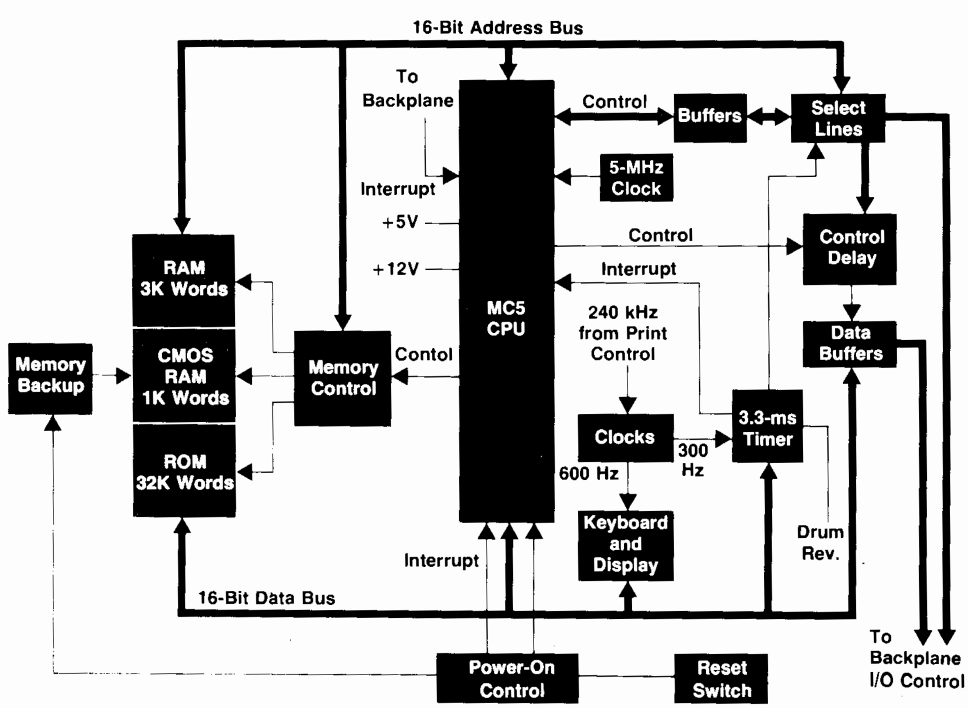



**Fig. 1.** *Machine control system of the 2680A Laser Printer controls drum rotation, paper movement, the operator interface, print density, diagnostics, and other functions.*

the active task in a wait state. The suspended task reawakens (enters the ready state) when the suspend time it specified has elapsed. An active task issues a SCHEDULE function when it wishes any other task to enter a wait state with a specified wait time. A DEACTIVATE function call issued by an active task causes a task to enter the dormant state.

The operating system also provides an orderly process for sharing a resource among many tasks. An example of a shared resource is the analog-to-digital converter (ADC) used in the 2680A. An analog multiplexer on the input of the ADC provides input from many sources, and many tasks use the ADC. When a task wants to use a shared resource it issues a SYNCP function call. The calling task is then suspended and its request is queued for the shared resource. The shared resource processes that task's request after processing all the earlier requests in the queue. The requesting task is then reactivated and given the required information from the shared resource.

To minimize operating system bookkeeping overhead, a linked list data structure is used. Tasks are linked with other tasks in the same state. Each task is represented by a block of memory called a task control block (TCB), which contains the information needed to specify a task and its state (Fig. 2). When a task is scheduled its TCB is linked with other TCBs of the same delay time.

There is a circular array of linked list pointers called list heads, with each pointer representing a certain time delay or time slot (Fig. 2). A time pointer points to the list head

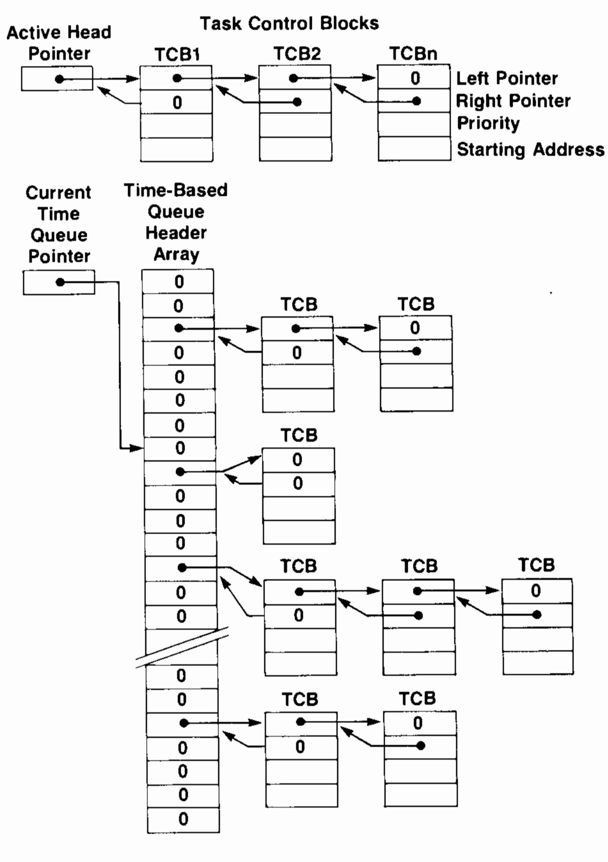



**Fig. 2.** *Machine control system operating system data structures.*

representing the current time period. The list head points to the list of tasks ready to execute. At the beginning of each new time period, the operating system advances the time pointer to the next list head. All suspend times are measured relative to the current time pointer. For example, if a task suspends for five time periods, the task's TCB is linked into the list five periods ahead. The maximum suspend time is therefore represented by the size of the circular array of list heads.

Tasks pointed to by the time pointer are in the ready state and are waiting to execute in the current time period. Tasks are positioned in the linked list according to priority information contained in their TCBs. The highest-priority tasks are executed first. If a time period expires before all tasks in the ready state are executed, the remaining tasks are merged into the next list. Low-priority tasks may be pushed back one time slot.

### Printing Control

The printing process requires the MCS to perform precise control and timing of a number of machine processes and to synchronize the printing process with the data control system (DCS). See last month's issue for a description of the DCS. A communication protocol is used by the MCS and the DCS to control the flow of pages through the printer. When the DCS has a page ready to print it signals the MCS to start the printing process.

Before the printing process begins the machine must be conditioned for printing. This preconditioning involves such things as warming up the laser, turning on the vacuum system, and starting the laser scanner motor. The preheater is also warmed up and the stacker is positioned to its starting point. The drum is then rotated and its surface potential is adjusted for printing.

Many events during printing require that certain actions be performed at specific drum positions. A drum control task synchronizes events with the rotating drum.

There is 432 mm of usable print area on the 503-mm drum surface. This is enough to print two standard 8½×11-in pages on each drum rotation. The remaining 71 mm is used for electrophotographic process control and the drum seam. During printing, all pages must be within the 432-mm print area. When the DCS has a page to print, a page placement task monitors the drum position and determines when to start the page. When the drum is in the correct position, the MCS signals the DCS to start passing data to the laser.

The page placement task must also furnish information about page placement on the drum so that transfer of the print to the paper can take place at the correct time. The transfer station is approximately one-half drum rotation from the laser position. The transfer control task uses the page placement information to calculate when to start the transfer process.

The transfer control task runs the process of transferring the image from the drum to the paper. This involves the precise control and timing of paper movement, the transfer corona, fusing, and output paper tensions.

After a page is transferred to paper the MCS notifies the DCS that the page was successfully printed on the drum and transferred to paper. The DCS can then release that page from its memory.

# Sensing Paper Jams

**by Gary L. Holland**

The 2680A Laser Printer's paper drive mechanism provides a means for monitoring paper speed and for detecting and terminating abnormal paper motion. The mechanism uses fewer components than methods previously used by high-speed printing devices. Its advantages include higher reliability, lower initial expense, and simpler paper threading.

Fig. 1 is a block diagram of the elements of the paper control and detection system. The speed of the output motor is monitored by a tachometer, which provides a signal proportional to the speed of the motor. This signal is compared with reference voltages in the output motor drive circuit. If the output motor is revolving at an abnormal speed, either a jam-slow detection signal or a jam-fast detection signal is generated. A jam-slow detection signal indicates a paper path obstruction, while a jam-fast detection signal indicates either that the paper has pulled out of the input tractors or the output pinwheels, or that the paper has torn.

The machine control processor described in the accompanying article supplies a maximum-current signal to the maximum-current circuit. This signal sets the magnitude of the current through the output drive motor under normal running conditions. The speed-limit circuit reduces this current to maintain the speed of the motor at a predetemined percentage of normal printing speed, typically 110 percent, when paper is ejected from the printer at the end of a box. The outputs of the maximum-current circuit and the speed-limit circuit are applied to an analog OR gate, which sets the motor-current drive signal to the lesser of the maximum-current circuit output or the speed-limit circuit output.

### Speed Limit Scheme

When the paper offers no resistance to the output motor, the speed of the motor tends to increase to an unacceptable level. To prevent this, the speed of the motor is monitored by the tachometer, and if it becomes too high, the speed-control circuit decreases the current through the motor until a preset speed is maintained. This preset speed, at which the speed loop takes over, is faster than normal print speed, but not so fast that inadequate fusing results.

In the speed-limit circuit, the output of the tachometer is low-pass filtered to remove ripple and then compared to a preset level. An error voltage is then input to a compensation circuit which makes the speed-control loop stable and gives it adequate response time. The output of this compensator pulls down the input to the final buffer amplifer to whatever level is needed to balance the power to the motor with the power required to keep the paper moving at a constant speed.

### Jam Detection

The jam-detection circuitry in the speed-limit circuit might more properly be called speed-indication circuitry, since the machine control processor must have more information than this circuitry gives to detect a paper jam. The circuit simply compares the output of the low-pass-filtered tachometer signal with a low level to see if the output motor is stopped. If it is stopped, the jam-slow signal is asserted. If the machine control processor knows that the paper should be moving and it sees this signal asserted, it knows that there is a jam condition. The other jam signal, jam-fast, is asserted whenever the speed loop is pulling down the input to the final buffer amplifier. This tells the processor that the paper is not exerting the usual force on the output tractors, which usually means that the paper has pulled out of the input or output tractors or that it has torn. In either case, printer operation is immediately stopped.

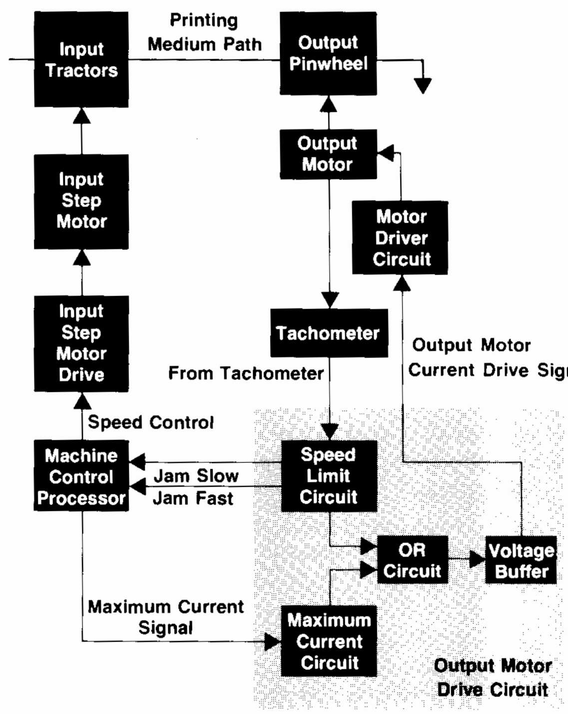



**Fig. 1.** *Paper jam sensing system block diagram.*

## Keyboard and Display

The operator keyboard, the numeric keyboard, and the 20-character alphanumeric display provide the operator and service engineer with a convenient interface to the printer. The operator keyboard is used to load paper, move the stacker, adjust print registration, eject paper, and print. the alphanumeric display assists the operator by providing information about the state of the machine. The service engineer has access to diagnostic programs and troubleshooting information using the numeric keyboard and the display.

## Paper Movement System

The paper movement system controls and monitors the movement of paper in the printer. This system consists of an input step motor, an output tension motor, a position encoder, and a paper jam detection circuit.

The input step motor controls the flow of paper through the machine. A relative-position encoder on the input motor shaft provides feedback to the MCS. This system is designed to keep the paper in registration with respect to print transfer and top of form. During printing the paper position is continually monitored and corrected if necessary so that proper print registration is maintained.

The output paper tension motor applies tension to the paper. The tension value is adjusted according to the needs of various printing conditions. When paper is first started the tension is set to a high value to overcome the static friction of the paper. After the paper is started the tension is dropped to a medium value for printing. When the paper is stopped the tension is reduced to a low standby level.

The output tension motor is also used to detect paper jams (see page 13). The motor contains a tachometer which indicates the tension motor speed. During printing the tachometer is monitored by the MCS to detect jams. If the output tension motor speed is not close to the normal paper movement speed then a possible paper jam condition exists.

### Stacker System

The paper stacker system is designed to stack paper automatically during printing and to be used manually by the operator when loading or removing paper. When the machine is not printing the operator can control the stack table using the stack up and down keys. During printing the stacker moves automatically, governed by a special algorithm, to compress the paper stack.

### Diagnostics

The first and most important goal of the diagnostics is to minimize the troubleshooting required of the HP customer engineer (CE) when the unit fails, thereby decreasing the mean time to repair (MTTR). It was always foremost in our minds that this product is very complex and uses technologies that are new to HP's service force. Since electrophotography has its historical origins in office products and since the CEs servicing the 2680A are accustomed to dealing with data processing equipment, efforts were made to make the 2680A look as "digital" as possible. Whenever feasible, the diagnostics locate a failed assembly or small set of assemblies and do not require the CE to interpret electrophotographic data.

A second goal of the diagnostics is to reduce the number of special tools and tedious adjustments necessary to service the machine. Sensors included in the system for reliability reasons are used by firmware routines to perform calibrations and adjustments. Procedures that require use of electrostatic potential, development density, and laser beam power measurements are automated by firmware using built-in sensors, eliminating the need for special measurement tools.

A third goal is customer satisfaction. The data processing environment puts some special demands on an electrophotographic device. Typically in the use of a copier, an operator is standing close to the machine when it is printing. If print quality degrades, the problem will be detected almost immediately. The data processing environment, however, is characterized by long periods of unattended operation. Also, the user who is most concerned with the quality of the print may not actually receive the output until long after it is printed. Therefore the printer must be capable of detecting degradations in quality before they become noticeable.

A fourth goal, related to the previous one, is that the diagnostics should facilitate detection of slowly degrading parts. Since a large part of the cost of servicing a product is in travel to the customer's site, it is helpful if the unit can tell a CE on site what is about to fail so that it can be replaced, saving a separate trip to the site. On the 2680A, data relating to drum potentials and development measurements appears on the diagnostic printout. This data can provide early clues to degradation of the drum or the developer mixture.

Finally, the diagnostics provide tools that were used by the product development team to speed the development of the product. Many of the important operating parameters of the machine were stored in nonvolatile random-access memory and could be changed by entering commands on the numerical keyboard. Thus the operation of the machine could be altered for experiments without having to reprogram the ROM. As the hardware design solidified and the product neared production, many parameters were moved into ROM.

These five goals led to a dual approach to diagnostics on the 2680A: a structured, on-line fault detection system and a set of flexible, off-line, interactive tools.

The on-line fault detection system can detect and report 124 different fault conditions. This system represents the largest portion of the diagnostics in the 2680A machine control system. Most of these diagnostics run continuously as the machine is printing.

Besides adding cost, the addition of sensors and corresponding firmware in the implementation of a fault detection system can potentially decrease the reliability of the overall system by increasing its complexity. To minimize this effect, the 2680A diagnostics take advantage of redundancies in sensing to provide checks on the sensors themselves.

For example, consider a failure of the primary corona power supply. The processor continuously monitors the current to the corona device and the voltage on the primary corona screen. A failure of the power supply first appears to the processor as irregular values for these measurements. The primary corona is used for conditioning the drum, that is, placing a uniform electrostatic potential on it. Therefore the measurement of drum potentials using the electrostatic monitor provides a redundant check on the corona diagnostics. A failure of the primary corona supply causes illegal drum potentials to be measured after some delay caused by the rotation of the drum. The electrostatic closed-loop system attempts to correct the potentials by adjusting the setting on the corona power supply. Since the system is unable to correct the error and the potentials are such that poor print quality would result, the 2680A stops printing with the message, "Hardware Malfunction." A keyboard command can be entered to display the fault message which identifies the primary corona supply as the failed assembly. If a condition had occurred such that the primary corona current and voltage sensors detect a fault but the drum potentials remain in the acceptable range, the 2680A will not stop running and no message will appear. A service representative can enter a command on the numerical keyboard that causes warning messages to appear under these conditions.

### Flexible Service Tools

The other approach to diagnostics was to provide a set of flexible tools. By providing a basic set of capabilities that use the numerical keyboard and 20-character LED display, the firmware allows service personnel to deal with failure situations that were not anticipated when the diagnostics were designed. As more is learned about the servicing of the machine from field experience, service procedures can be changed for improved efficiency without altering firmware.

The service keyboard functions are implemented using three-digit keystroke sequences. Access to some of the sequences is controlled by requiring the entry of an access code before certain command sequences will be recognized. The access code is not so much a security feature as a means for protecting the operator from inadvertently altering the operation of the machine or even damaging it.

One class of command sequences allows the display of machine parameters and measurements. Measurements made with the analog-to-digital converter can be viewed, as can running averages of certain measurements. The status of control loops can be displayed to show loop targets and controller settings. Counters that track the age of replaceable parts and the time since the last preventive maintenance can be viewed. Certain parameters stored in nonvolatile memory can also be entered as data from the keyboard.

Another type of command sequence can break control loops or disable certain sensors or diagnostics. Analysis of the electrostatic control loop is facilitated by the ability to break the loop and adjust corona settings. A failed sensor can sometimes be circumvented by disabling the diagnostic that uses the sensor, allowing printing to continue until the sensor can be replaced.

Direct control of certain electrical and electromechanical devices in the 2680A can be obtained using the device on/off commands. Solenoids, motors, power supplies, and lamps can be turned on and off individually or in arbitrary combinations by using these commands.

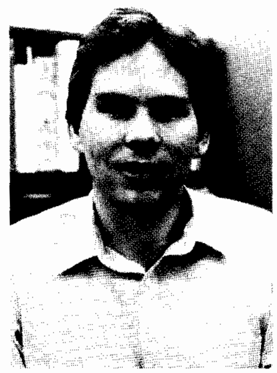
There is also another class of commands that provides miscellaneous tools or automated service procedures. For example, one command displays a log of fault messages that have occurred since the last service call; this can reveal intermittent problems. Another command automates the task of lubricating a newly installed photoconductive drum with toner, prompting the service representative whenever intervention is necessary.

One of the commands that can be entered by the operator is the self-test command. This command causes a printout that can be used for evaluating print quality and that records various measurements and parameters. The self-test diagnostic philosophy on the 2680A is somewhat different from that of other HP printers. The self-test on other printers is a collection of diagnostics which are run only when self-test is invoked. As mentioned above, the fault-detection programs on the 2680A run whenever the machine is printing. Therefore, self-test invokes very few tests that don't run when normal jobs are printing.

Altogether the 2680A provides 190 keyboard commands: 84 display commands, 16 modify commands, 14 disable/enable commands, 48 device on/off commands, and 28 miscellaneous tools.

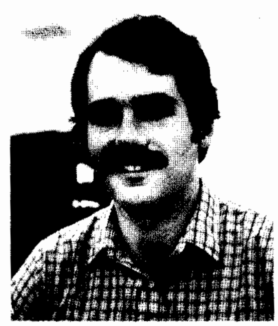
### Reference

1. B.E. Forbes, "Silicon-on-Sapphire Technology Produces High-Speed Single-Chip Processor," Hewlett-Packard Journal, April 1977.



**Von L. Hansen**

Von Hansen was born in Smithfield, Utah and received his BSEE degree from Utah State University in 1976. He joined HP the same year and helped develop the machine control system of the 2680A Laser Printer. Now a project manager with HP's Boise Division, he's a member of the IEEE and is listed as an inventor on two pending patents on 2680A paper control. In 1980 he received his MSEE degree from Stanford University. Von is married, has four children including a set of twins, and lives in Boise, Idaho. He's a member of the Toastmasters speaking club and a small local orchestra, is involved in church work, and enjoys photography, gardening, and woodworking.



**James D. Crumly**

A graduate of Stanford University, Jim Crumly received his BS and MS degrees in electrical engineering in 1976 and joined HP the same year. He helped design the 2680A corona power supplies and densitometer and worked on the control and diagnostic firmware. He's now a project manager with HP's Boise Division and is a member of the IEEE. Jim is married, has a daughter and lives in Boise. His interests include soccer, skiing, gardening, and Koiné Greek.