DECEMBER 1978

HEWLETT-PACKARD JOURNAL

Easy-to-Use, High-Resolution Digitizer Increases Operator Efficiency

This advanced new microprocessor-controlled digitizer provides an accurate, speedy, and convenient method for entering position information from maps, slides, x-rays, photographs, and other media into a computer for analysis.

by Frank P. Carau

HAVE YOU EVER NEEDED to enter coordinates from an oscilloscope photograph into a computer for analysis? Or if not from a photograph, perhaps from a map, a graph in a book, a strip chart recording, a 35-mm slide, a mechanical drawing, or a schematic? In any case, what you needed to perform that task was a digitizer.

A digitizer is a device that transforms graphical data into planar coordinate information that can be read and understood by a computer. These coordinates are usually presented as X and Y coordinates based on the position of a cursor on the surface, or platen, of the digitizer. The cursor has a viewing area with a crosshair for alignment with the point of interest on the document, and is coupled either mechanically or electrically to a position sensing device that provides the positional information to the computer.

Advanced Digitizer

Model 9874A Digitizer is a powerful new portable digitizer that offers significant increases in performance and reliability, and simplified operation through 'work-station' design and human engineering. The 9874A (Fig. 1) is designed to provide flexibility, high resolution, and simplicity of use in a wide range of applications using different source media. It has many new features, including a tiltable working surface, rear projection capabilities, a cursor vacuum system, built-in self test, HP-IB* interfacing, automatic document alignment and axis extension, microprocessor control, and a multiple-function user keyboard.

The HP 9874's capabilities are matched to a number of industrial applications, such as a local utility developing a computer model of a pipeline network, a government agency recording data on crop acreage, or a lumber company estimating harvest yields. Other applications include clinical medicine and electronic design. Present digitizer users who would find the 9874A of particular interest include hospitals and clinics, the military, surveying and mapping firms, manufacturers of electronic equipment, agricultural and forestry services, universities, and research and development laboratories.

Cover: *Model 9874A Digitizer transmits coordinate data to an on-line computer. Its tiltable, translucent platen adapts to a variety of media, including backlighted and rear-projected images. An EXTEND mode is provided for digitizing media larger than the platen. (Aerial photo courtesy of the U.S.A. National Aeronautics and Space Administration).*

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*Hewlett-Packard Interface Bus (IEEE-488, ANSI MC1.1)

Fig. 1. *Model 9874A is an advanced microprocessor-controlled digitizer that provides 25-μm resolution and ±125-μm accuracy. Its adjustable glass platen accommodates a variety of media. The keypad helps the operator control the digitizer/computer system.*

Problems of Digitizing

Many digitizing difficulties arise because digitizing is an operator-intensive function. It requires the user to perform a mechanical control function at the digitizer and maintain control of the computer system at the same time, without removing attention from the digitizing unit.

The primary problem of digitizing is user fatigue. The process of spending hours bending over the digitizing surface accurately positioning the cursor can cause severe problems in operator attention and fatigue. The new HP 9874A digitizer incorporates several features that help reduce these problems.

A major feature is the tiltable platen. By allowing the operator to position the platen anywhere between 17 degrees and vertical, a significant comfort factor can be achieved that would not be possible on other digitizers without special props or mechanical supports.

A second significant feature is the design of the cursor, which incorporates several enhancements that help reduce operator fatigue and reduce error in the digitizing process. The first is an operator controlled vacuum system that allows the operator to cease digitizing and lock the cursor to the platen while answering the phone, checking progress, or simply resting arms and eyes for a while. Another enhancement is the design of the crosshair. The usual digitizer crosshair consists of intersecting lines of approximately 250-micrometre width (see Fig. 2a). With the resolution and accuracy of the 9874A (25 micrometres and ±125 micrometres respectively) crosshairs of this design would entirely cover the accuracy window. The 9874A crosshair provides a doughnut target of 375-micrometre outside diameter with a center hole of 250-micrometre diameter (Fig. 2b). Tests have demonstrated that an operator can repeatably position this crosshair design within 50 micrometres of the known position. Thus the digitizer can be used up to its full specified accuracy limits.

A third feature of the cursor is the fact that the crosshairs are edge lighted for greater visibility. This can be of significant value when digitizing documents with a dark background, or in which there are multicolored lines and high-density information. Increasing the visibility of the crosshairs reduces operator eye fatigue and increases the accuracy of the positioning process.

The second major problem faced by a digitizer user is that of controlling the computer system. Since the user is stationed at the digitizer, it is inconvenient to move to or reach the computer keyboard to enter numeric parameters, see cues, or change program modes or functions. This can be especially inconvenient in situations where significant interaction or frequent mode changes are required. The 9874A makes a significant contribution to user control of the digitizer/computer system by using a work station concept, in which control of the entire computer system is available from the digitizer. Thus the problem of the user's transferring attention from the digitizer to the computer is alleviated. The work station con-

Cursor Technology

by Henry T. Hetzel

In the new Model 9874A Digitizer, the cursor acts as the second plate of a capacitor formed between the platen traces and the cursor pickup. The simplest type of cursor pickup is an open plate, as shown in Fig. 1a. This design has certain drawbacks, the primary drawback being sensitivity to stray electrical fields from outside sources. These stray fields can cause severe errors in the digitized data.

To eliminate this problem in the 9874A, an aperture technique for capacitive pickup was developed. In the aperture technique an electrically grounded flat conductive sheet with a hole in it defines the area from which electric fields are allowed to pass to the collecting, or pickup plate. The top of the pickup plate is also protected by a solid grounded sheet (see Fig. 1b).

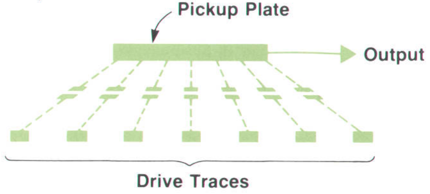
This scheme is incorporated into the glass viewing area of the 9874A cursor. What appears to be a single layer of transparent glass is actually a composite of three layers of glass bound together with optical cement. Each layer is coated on its top surface with a thin film of transparent indium oxide, which is electrically conductive. Crosshairs are etched into the bottom surface of the bottom layer and filled with orange epoxy paint. An 18-mm-diameter hole is etched through the indium oxide film on the top surface of this same layer of glass. This aperture hole is concentric with the crosshairs within 12 micrometres. The indium oxide layer on the top of the middle layer is the signal collecting plate, and is shielded from above by a grounded indium oxide film on the top layer of glass. These three layers are then cemented together into a single unit (Fig. 2). Electrical connections to the layers are made at their edges inside the doughnut-shaped body of the cursor.

Since both the top and bottom layers are grounded, signal fields entering the hole in the bottom indium oxide layer are well protected from external influences, such as the operator's hands, which could distort the field or inject spurious signals.

Transparent indium oxide films were necessary to keep the cursor viewing area open. An alternative would have been to use a large signal collecting ring near the circumference of the cursor. This would have allowed unobstructed viewing without the need for transparent films, but because the entire ring would have been required to stay within the active area of the platen, the digitizing area would have had to be reduced by a large border corresponding to the ring's radius.

Another feature of this cursor construction is the accuracy with which the hole defining the signal area is aligned to the crosshairs. A standard photolithographic process is used to etch the indium oxide, but the critical step of masking the hole onto the photoresist-covered part is done on a precision spindle that rotates the work under a high-power microscope. Adjustments are made to center the crosshairs and the mask on the axis of rotation. The procedure eliminates parallax in the aligning process, which could otherwise have developed through the glass thickness. Once etched into the indium oxide, the hole is permanently fixed relative to the crosshairs because they are both on the same piece of glass. Thus the accuracy of the cursor cannot be changed through mishandling, short of destruction of the cursor lens.

A. Open Plate



B. Enclosed Plate with Aperture

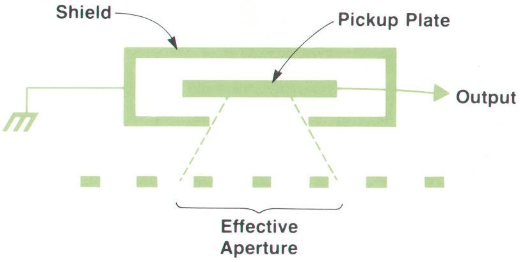


Fig. 1. *Open plate pickup design (A) is sensitive to stray fields. 9874A cursor (B) uses an enclosed plate with an aperture.*

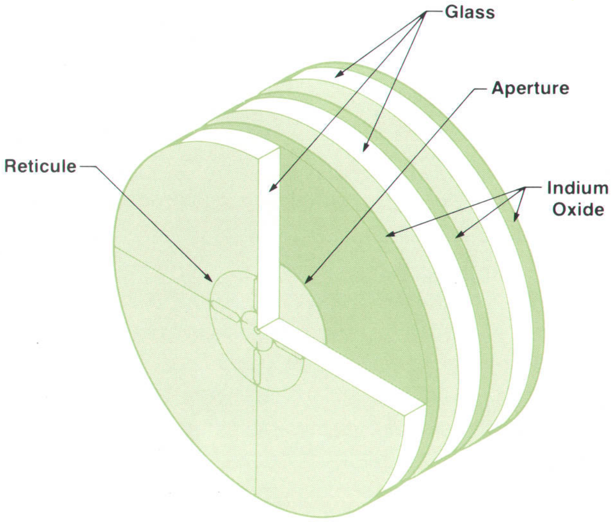


Fig. 2. *9874A cursor consists of three layers of glass with conductive indium oxide layers for the pickup plate and shield.*

cept is implemented by means of a multipurpose keypad and display on the right side of the 9874A. This keypad allows the user to select the digitizer mode and enter numeric data, and provides for feedback via the computer-controlled display functions. User control of the computer is facilitated by the special function keys, which can be programmed to provide a high degree of interaction between the user and the computer.

Another digitizing problem is media compatibility. Digitizing media come in all shapes, sizes, and types, from maps to strip charts to photographs to 35-mm slides. The 9874A provides maximum built-in flexibility to allow the user to interface simply to various media. The adjustable working surface is ideal for flat documents. An optional strip chart box and a slot

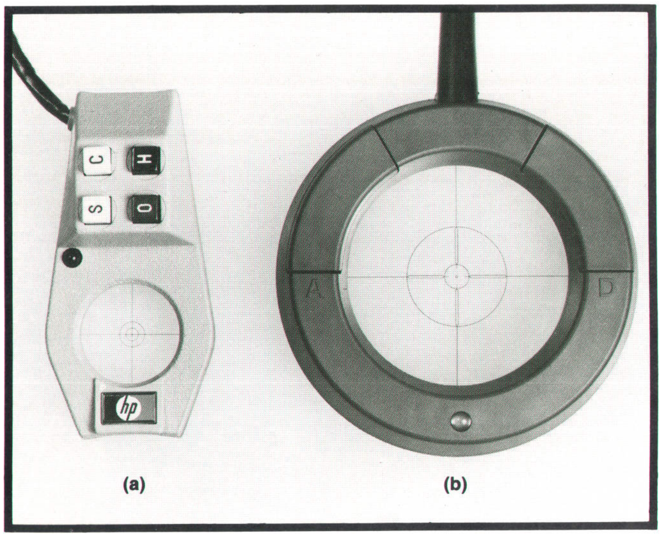


Fig. 2. *Old digitizer crosshair design (a), with intersecting lines ~250 μm wide, would cover the entire accuracy window of the new 9874A Digitizer. New 9874A crosshair design (b) provides a doughnut target with a 250-μm center hole.*

under the keypad can be used for very long strip charts. The EXTEND mode allows very large documents to be moved across the platen while maintaining the coordinates established on the document. The glass platen allows the digitizing of projected transparencies directly, and the user can set up a lamp behind the platen to digitize documents requiring backlighting, such as x-rays.

To provide feedback to the user about present position, mode of operation, error conditions, and commands for user operations, the 9874A has multiple feedback modes. These improve the user's efficiency by more tightly closing the loop between the user and the computer. The programmable display can provide positional feedback, numeric cues, and a limited alpha capability. A more significant feedback mode is achieved with a variable frequency tone that can be programmed to provide many types of information. Some examples are: various tones to specify which point in a sequence the user has digitized, tones with frequency proportional to distance to guide the user to a point or line on the digitizing surface, multiple-frequency error tones to signal various error conditions of greater and lesser importance, and different tones for cueing various tasks. Since the user's attention is normally focused on the digitizer surface, this feature can be very valuable, in that the user can be provided feedback or instructions without removing visual attention from the document surface. This reduces fatigue and increases operator efficiency.

Hardware Design

It took a significant technology effort to develop the 9874A to meet the stringent accuracy and environmental specifications. This effort centered on three major areas: the digitizing technique, the platen construction, and the cursor construction.

For the digitizing technique there were four major design goals: achieve the required resolution and accuracy, minimize environmental effects, minimize the complexity of the platen construction, and provide an absolute coordinate system, a system in which the cursor can be removed from the platen and still know its position relative to the origin when it is replaced.

The first decision was to use a capacitively coupled or electrostatic drive technique. The platen contains a grid of closely spaced horizontal and vertical conductive traces. These are driven with a voltage signal, and this signal is coupled from the platen traces to the cursor pickup by a small equivalent capacitor formed between the trace and the pickup disc (Fig. 3). The pickup from each trace is related to the effective capacitance between the trace of interest and the pickup plate within the cursor. This capacitance is a function of the distance from the cursor to the trace. Thus traces close to the cursor have relatively large coupling capacitances while traces farther away have lower coupling capacitances. If the cursor pickup is terminated in a capacitive load and a high-input impedance amplifier, a weighted sum of the drive signals from the various traces can be obtained (Fig. 4). If C_L is the load capacitance and if $C_L >> C_1, C_2, \ldots, C_N$, this sum can be computed as:

$$V_o \approx \left[(C_1/C_L)V_1 + (C_2/C_L)V_2 + \ldots + (C_N/C_L)V_N\right] \quad (1)$$

This can be reduced to:

$$V_o \approx \left[C_1V_1 + C_2V_2 + \ldots + C_NV_N\right]/C_L \quad (2)$$

Equation 2 shows that the cursor voltage resulting from a particular trace is directly proportional to both the drive voltage and the coupling capacitance between the cursor and that trace. Thus the total resultant output voltage is a weighted sum of the various trace drive voltages based on the distance from the cursor to the individual traces.

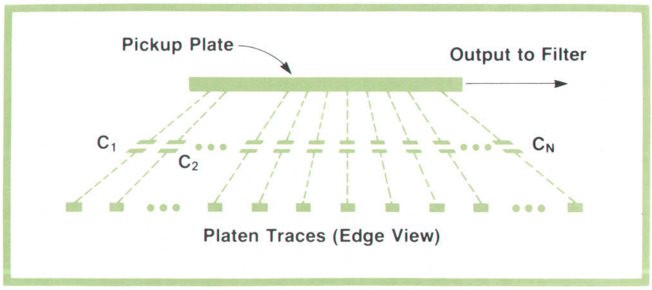


Fig. 3. *9874A platen contains closely spaced traces driven by a voltage signal. Trace signals are coupled to the cursor pickup by the trace-to-pickup capacitances.*

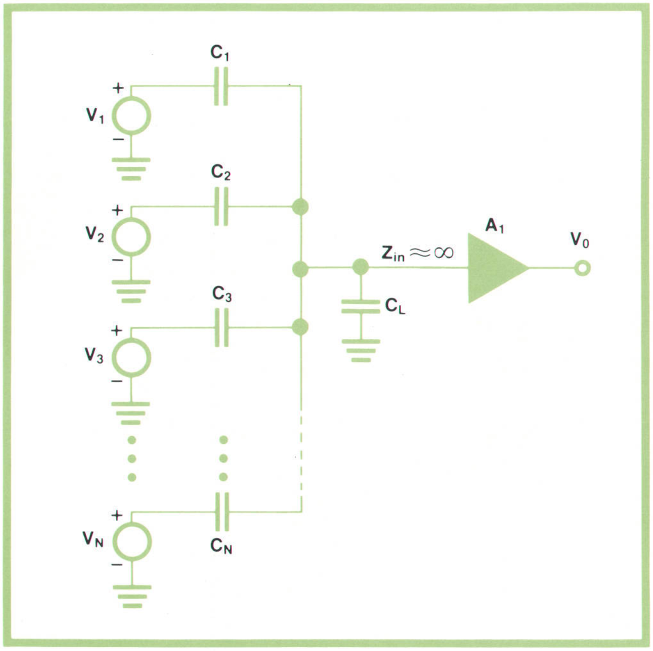


Fig. 4. *Equivalent pickup circuit showing trace drive signal sources, equivalent pickup capacitances, and the cursor equivalent load capacitance.* C_L *is the sum of parallel parasitic capacitances and a fixed capacitor put there to guarantee that* $C_L >> C_1, C_2, \ldots, C_N$.

The next step is to create a technique for driving the individual traces that takes advantage of this coupling process. If we sequentially drive each line high for a short period of time and then drive it low we will see a series of weighted pulses coming out of the cursor pickup such that the closest trace has the maximum pulse amplitude. However, dealing with a sequence of amplitude-weighted pulses is difficult and a more convenient technique is desirable. If we drive each trace high and hold it high while subsequent traces go high we will see an output that is a weighted series of steps up to the final, maximum level (Fig. 5). Knowing the velocity with which the wave is travelling across the platen we can measure the distance to the cursor from the first trace on the platen by measuring the time between the start of the wave on the first trace and the midpoint of the rise of the cursor signal. This edge measurement is much simpler to deal with than the pulses. However, another refinement significantly aids the system design. If after driving the traces high we later bring the traces low sequentially such that the drive signal becomes a cyclic wave we can create a cyclic output wave that contains the positional information in its leading and trailing edges. We can then simply measure the distance from the first trace to the cursor by measuring the phase difference from the first-trace drive signal leading edge to the cursor signal leading edge. This is the method used.

Implementing the Digitizing Technique

The easiest way of generating time-delayed cyclic signals is to use a shift register. The desired cyclic signal is fed into the input of the first stage, and the clock frequency determines the delay between the various stages. Thus, for the design discussed above, a square wave of suitable frequency (in our design f=5 kHz) is fed into the shift register input and clocked across at a clock rate that makes the wavelength longer than the platen size. This is to avoid phase ambiguity that would occur if more than one cycle appeared on the platen.

The cursor signal is buffered by a high-impedance amplifier and then fed into a bandpass filter. This filter removes the higher-order harmonics in the pickup wave and provides a sine wave output. Because of the effect of summing many weighted signals from the traces, the phase of the filtered pickup signal provides a smoothly varying representation of the cursor position. This makes it possible to interpolate between trace positions and realize system resolution much finer than the trace spacing. The filter output is then run through a zero-crossing detector that produces a square wave output with the phase information of the pickup wave contained in its transition points. Position information is then obtained by

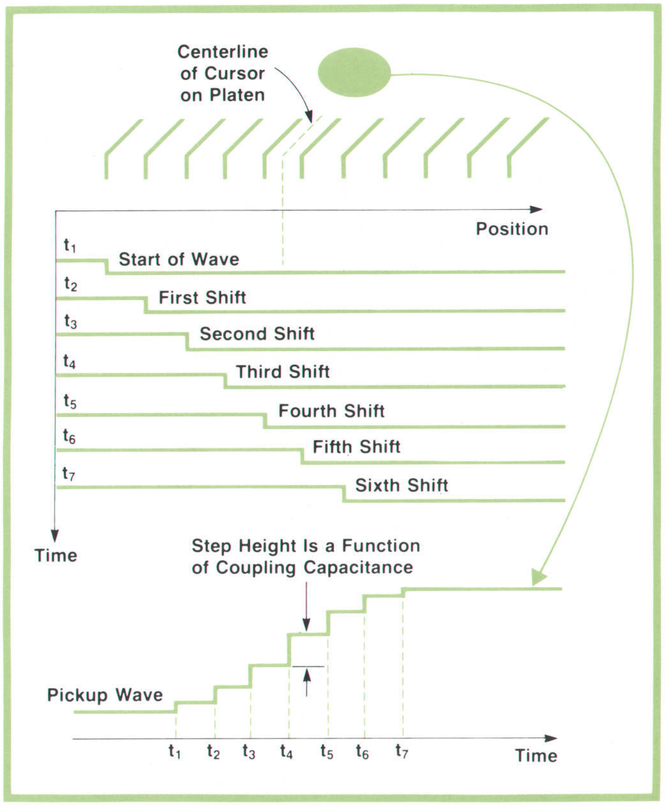


Fig. 5. *If each platen trace is driven high and held there while subsequent traces go high, the pickup wave at the cursor output is a weighted sum of step functions. Distance of the cursor from the first trace is proportional to the time from the first-trace step to the midpoint of the rise of the cursor signal.*

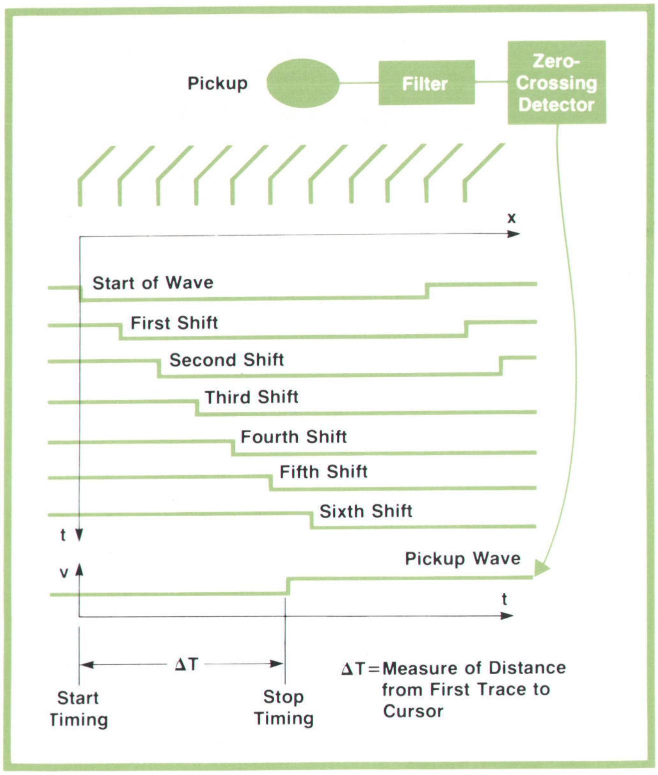


Fig. 6. *In the 9874A Digitizer the platen traces are driven high sequentially and later driven low sequentially, creating a cyclic cursor output signal. This is filtered to produce a sine wave, from which a zero-crossing detector extracts the desired phase information.*

measuring the time delay (or phase difference) between the rising edge of the first-trace waveform and the rising edge of the processed cursor pickup waveform (Fig. 6).

One problem frequently encountered in electronic systems is drift. This is a variation of a parameter or a component value caused by changes in temperature, humidity, or aging. In the system described above drift comes primarily from changes in the filter phase delay and in the zero-crossing detector error. One useful way to minimize the effects of drift is to make the measurement differential rather than absolute, that is, to make a measurement that represents only those parts of the measurement that may include drift, and then subtract that measurement from the measurement of the total system. In the 9874A we do this by performing a second measurement that we call the reference measurement. In the reference mode the output of the shift registers that drive all of the platen lines are all shifted high or low at the same time. Thus the time delay measured is the same for any cursor position on the platen, whether the cursor is over the first trace, the last trace, or in the middle of the platen. This measurement is retained in the processor, and when a real position measurement is made with the shift register outputs time delayed across the platen, the reference measurement is subtracted from the position measurement to obtain a differential result with all components that may contain drift cancelled out.

Increasing Resolution

A limitation of the digitizing technique described above is the resolution with which the phase delay between the first-trace wave and the cursor pickup wave can be measured. Practical considerations limit the phase resolution of the system to 0.1 degree or 1/3600 of a cycle. With the size of the platen set at 430 mm the positional resolution of the system is:

$$(430\text{ mm})(1/3600)=0.1194\text{ mm}=119\text{ micrometres.}$$

The desired positional resolution of the system is 25 micrometres, or about 1/5 of that provided by this drive technique. This could be overcome by increasing the phase resolution of the system. However if it ever becomes desirable to expand the platen area this limitation will become severe. Fortunately, the drive as described provides enough flexibility to overcome this problem. The approach is simply to keep the shift register input frequency (which establishes the center frequency of the filter) constant, but to decrease the frequency of the shift register clock (which establishes how rapidly the wave moves across the platen). This has the effect of creating multiple cycles of the drive waveform on the platen surface (Fig. 7). By physically shrinking the size of the waveform, but keeping the phase resolution the same, we increase

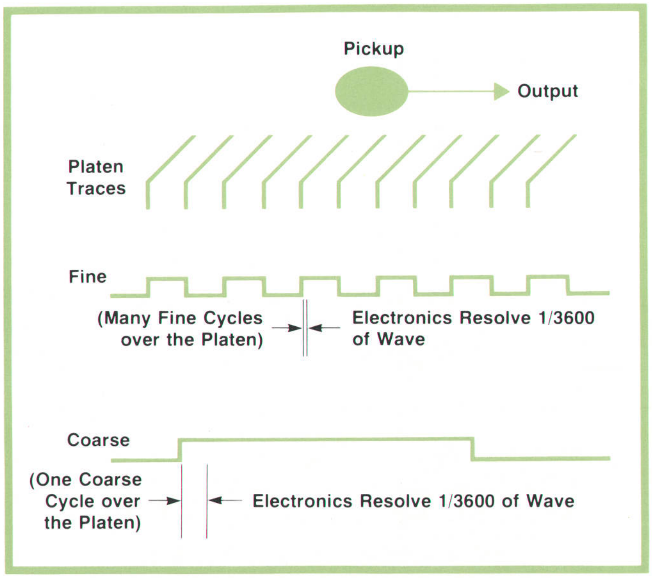


Fig. 7. *To attain the desired resolution the 9874A makes fine measurements with multiple cycles on the platen. A coarse measurement with only one cycle on the platen is made to determine which of the fine cycles coincides with the cursor position. A third measurement is used as a reference to eliminate the effects of drift.*

Glass Platen Technology

by Lawrence E. Brown

The glass platen of the 9874A Digitizer needs low-resistance, accurately positioned, environmentally stable X and Y circuit patterns to perform the digitizing function. The platen must also provide the user with a usable working surface, the ability to rear-project high-resolution images, and a delineation of the active digitizing area, all within a safe, reliable package.

To attain these objectives, glass was chosen as the substrate material. Two mirror-quality glass plates, called "lites", are used in the platen. The lites are specially ground, patterned, and laminated together to form the platen (see Fig. 1).

The top lite is lapped with an aluminum oxide paste on the upper surface. This frosted finish provides a sharp focal plane for rear-projected images.

Using special HP-developed tooling, a numerically controlled mill grinds the active area delineators in the lapped surfaces and the outside edges of the top and bottom lites. The machine produces smooth edges for safe handling and tightly controlled dimensions for accurate circuit pattern positioning. The ground lites are throughly washed and treated with an ammonium bifluoride solution to complete their preparation for the circuit patterns.

The production of the grid lines on each lite is a proprietary photolithography process. Three material layers are successively laminated to the circuit side of each prepared lite. These, in order, are: photosensitive adhesive, treated copper foil, and photosensitive film. The upper layer of photosensitive film is positively imaged using standard photoetch techniques and glass artwork masters to insure accurate grid lines, exposing the copper foil layer beneath. Using the now imaged top film layer as a resist, the copper layer is then etched away, exposing the photosensitive adhesive. The adhesive layer is then etched with the copper foil acting as a resist. This leaves a full pattern of three-layer grid lines. As a final step, the photosensitive adhesive layer, up to now unpolymerized, is exposed through the glass to be transformed into a hard polymer that permanently secures the foil to the glass. The grid lines have superior electrical resistance values similar to normal printed circuit traces.

The top film layer is removed only at the ribbon connector pads, and ribbon connectors are soldered to each lite. An X and Y pair of lites, complete with ribbon connectors, is tested electrically and then laminated together with transparent polyvinyl butyral resin, used to make auto windshields, as the center adhesive layer. This lamination step seals all the circuitry in the vinyl resin and creates a safety-glass platen.

Aesthetic embellishment is the final step in the platen process. Epoxy inks are screened on both lites to produce borders that mask the ribbon connector joints from the user.

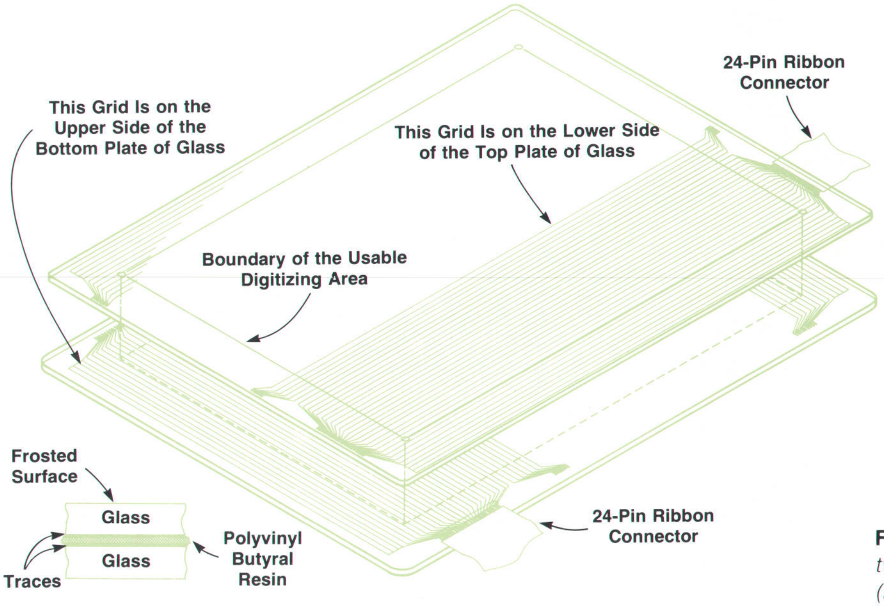


Fig. 1. *9874A platen consists of two mirror quality glass plates (lites) that are ground, patterned, and laminated together.*

the physical resolution of the system by the ratio of the spatial wavelengths of the two waveforms. For example, if the waveform that covers the surface has a wavelength of 430 mm, and the compressed waveform has a wavelength of 86 mm, the physical resolution of the compressed drive becomes

$$R = (86 \text{ mm}/430 \text{ mm})(0.1194 \text{ mm}) = 23.89\ \mu\text{m}.$$

This does present an ambiguity problem, in that compressing the waveform creates several positions on the platen where the measured phase is the same. This is resolved by driving the platen sequentially with both the full-platen-width wave, called the coarse wave, to establish the gross position of the cursor on the platen, and then with the compressed wave, called the fine wave, to provide the ultimate positional resolution.

This technique of coarse, fine, and reference measurements results in a system that provides absolute

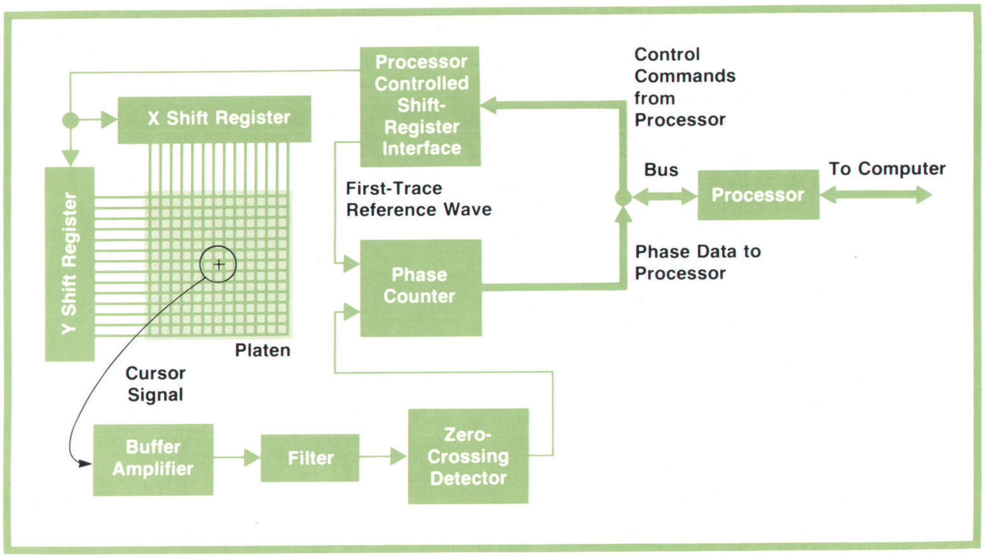


Fig. 8. *Model 9874A Digitizer block diagram. Shift registers produce the sequential platen drive signals.*

coordinates (the ability to lift the cursor and replace it without losing the origin), excellent environmental stability, and flexibility for later variations in platen format.

System Organization

Fig. 8 is a block diagram of the 9874A digitizing electronics. The shift registers are controlled by an interface unit that transforms commands from the internal processor into the correct drive waveforms for the drive mode selected. The cursor waveform is filtered and sent through the zero-crossing detector and on into the phase counter, which provides a digital word to the processor representing the phase difference between the leading edge of the first-trace reference signal and the processed cursor signal. The processor performs the algorithms required to sequence the digitizing process, interface to the other electronics (keypad, display, beeper, etc.), and communicate with the host computer.

Operation of the stylus, an alternative pickup device, is identical to that of the cursor. The tip of the pen cartridge, which extends beyond the stylus barrel, is used as the electrical pickup, equivalent to the pickup disc of the cursor. The waves are sensed and processed in the same way as the cursor, except that the equivalent pickup area of the stylus is much smaller than that of the cursor, so the signal strengths are greatly reduced. This increases noise effects in the resulting data, and parasitic media effects (see Inherent Problems of Digitizing, page 12) have a proportionally greater impact on the system accuracy.

Microprocessor Power

The digitizing technique and all of the user features were designed around the fact that a microprocessor would be used to make the 9874A a smart peripheral. The digitizing technique makes a single-axis position measurement that requires three distinct steps to obtain the final coordinate position. The power of the processor is used to perform these measurements for both the X and Y axes, and to minimize complications caused by this sequential measurement. The sequential technique significantly lowers the hardware cost of the system. However, measurement error is introduced if the cursor is moving during a measurement (Fig. 9a). This error is minimized by setting up the software to make the time difference between the X-fine measurement and the Y-fine measurement a minimum, since the X-fine and Y-fine measurements actually establish the system measurement performance. The software cycle for a full X and Y measurement is as follows:

X-coarse
X-reference
X-fine
Y-fine
Y-reference
Y-coarse.

Thus minimum time is spent between the X-fine and Y-fine measurements, and the appropriate reference measurement is made adjacent to each axis' coarse and fine measurements.

This technique minimizes cursor movement error, but there is still an error component present. The solution is to have the software compute the velocity of the cursor and offset the measurement to correct for the error caused by that velocity. The hardware measures the time between the previous point and the present point, t_1, and the time, t_2, from the measurement of the present Y coordinate, Y_2, to the present X coordinate, X_2 (Fig. 9b). By establishing the Y_2 coordinate as the reference to which the X_2 coordinate will be transformed we need only compute the X velocity to determine how much to shift the X_2 point to correct for the cursor motion. The X velocity

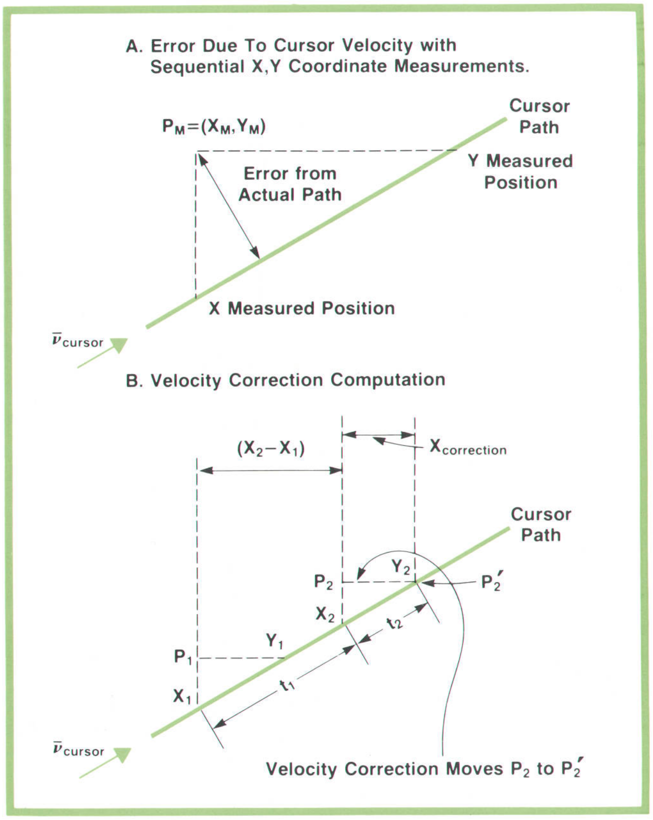


Fig. 9. *To compensate for cursor movement during a measurement, the microprocessor computes the cursor velocity and offsets the measurement accordingly.*

can be computed from the change in the X coordinate since the last X measurement, and from the time between measurements. The correction can be computed from the X velocity and the time from the X coordinate measurement to the Y coordinate measurement. Thus the X correction is found to be:

$$X_{correction} = (X_2 - X_1)(t_2/t_1) \quad (3)$$

and the corrected point P_2 is:

$$P_2 = ((X_2 + X_{correction}), Y_2). \quad (4)$$

This is only a first-order correction, that is, the correction will not be valid during acceleration. It has been found that when an operator is attempting to follow a line accurately by hand the acceleration and velocity levels are low enough that this correction factor produces an overall system error well below the position errors introduced by the operator in the digitizing process.

Another significant contribution of the processor is averaging of the signals during the digitizing process. This averaging takes place during each drive mode, that is, in the X-fine mode, many X-fine measurements are made before the mode is changed to Y-fine. In the 9874A each coordinate returned to the user is an average of 80 individual measurements. This reduces noise in the measurement process without a corresponding increase in hardware complexity.

Accuracy Results

The accuracy specification of the 9874A is ±125 micrometres over the platen surface. This is a composite that includes the accuracy of the drive system, the platen, and the cursor. Our tests of actual production machines show that typical accuracy in production units is running between ±62.5 micrometres and ±75 micrometres (see box, page 11). Final tests are set to a limit of ±75 micrometres to assure the user that the system will indeed meet the specifications of ±125 micrometres. Fig. 10 shows a typical accuracy plot of a production digitizer at 25°C and 50% relative humidity.

Software Enhancements Aid User

Another real contribution of a smart peripheral is its ability to aid the user in solving problems that are specific to that type of peripheral. The 9874A takes full advantage of the available processing power to provide simple solutions to several problems that can impact digitizer users.

The first of these problems is the alignment of the axes of the user's source document to the coordinate axes of the digitizer. In the past this has required either a long setup process or the generation of a computer program to transform the coordinates returned by the digitizer into the user's system. The 9874A performs these calculations internally. The user merely places the document on the platen, presses the AXIS ALIGN key, and digitizes the origin of the document coordinate system and a point lying on the X axis of the document. The internal processor then computes the transform matrix to go from the digitizer coordinate system to the user's coordinate system. All digitized points are then processed through that transform before being sent to the computer so that all points come to the computer in the user's coordinate system.

Another problem the user may encounter is a document too large for the platen of the 9874A. In this case the user can press the EXTEND button on the 9874A, and then digitize two points on the document that lie on the digitizer platen. The user may then move the document to any other position, including translation and rotation, as long as the two previously digitized points are on the platen after the motion is completed. The user then redigitizes the two reference points in the same order as they were initially digitized, and the processor calculates a new transform matrix that includes both the initial AXIS ALIGN and the later translation and rotation of the document.

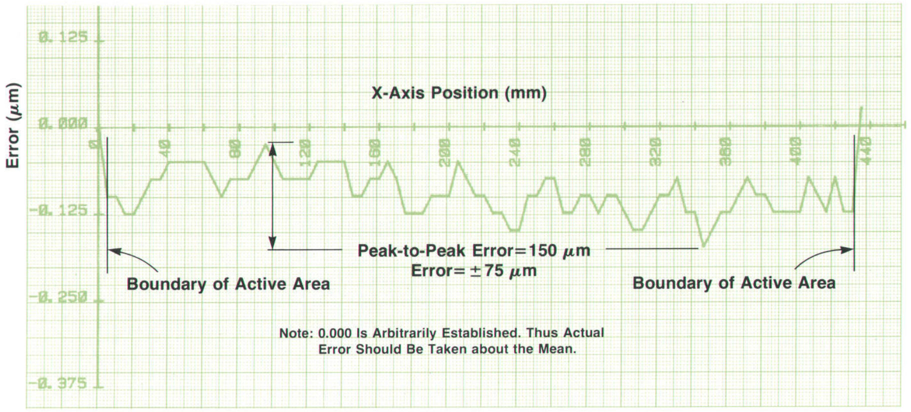


Fig. 10. *Typical production digitizer accuracy plot. Maximum acceptable error is ±75 μm, assuring that the accuracy specification of ±125 μm is met.*

Points digitized on the document in its new position on the platen are then automatically referenced to the user's coordinate system.

Digitizing is frequently done in a continuous mode, in which the user traces the line of interest and points are sent from the digitizer at a preset rate. In a real digitizing process, the user typically wants to select a new point a certain distance from the last point rather than a certain time after the last point. The 9874A provides the user with a choice of parameters, either time from the last point, or the vector distance from the last point to the next point. Both parameters may be specified by the user, with time variable from 20 ms to 32,000 ms in 1-ms steps, and distance variable from 100 micrometres to 514 mm in 100-micrometre steps. This eliminates the generation of a multitude of unwanted coordinates, and more closely ties the operation of the system to the user's desired result.

Another software enhancement for the user is the ability of the 9874A to understand a high-level graphics language on the HP-IB (IEEE 488). This provides the user with very flexible high-level commands to perform functions such as computer setup of the digitizer configuration, interrupt of the

Accuracy Testing

The 9874A Digitizer undergoes several levels of accuracy testing before being shipped. The first level of testing is at the assembled printed circuit board level. At this level all of the PC boards that impact system accuracy (including the platen drive boards, the filter board, and the phase counter board) undergo rigorous testing that guarantees that their operation will be within the limits required to provide the specified accuracy. The platen also undergoes electrical testing that ensures that each trace is electrically continuous.

When a digitizer has been assembled, another level of testing takes place. Four functional tests are run on each machine to ensure its operation within the specified limits. First, a repeatability test is run to ensure that the system noise is within the specified bounds. Next an axis skew setup procedure is run. 200 points are taken in a straight line along both axes. These points are fit to a straight line equation and the equations for each axis are compared to generate a correction for the skew, or lack of perpendicularity, between the two axes. This correction factor is set on the processor board and the test is repeated at a different platen location to verify that the correction is within the specified bounds. This correction sets the equivalent angle between the digitizer axes to within ±0.006 degrees. The next test is an absolute distance test. An F-shaped bar is used; the distance between the intersection points is approximately 250 mm and the actual distance between points is known within 2.5 micrometres. Ten point pairs are taken on each diagonal of the platen. These point pairs must be within ±75 micrometres of the known length of the bar to pass the test. This establishes that there is no scale error on the platen surface. The final test run on each machine is a point-by-point accuracy test in which 250 points are taken along a diagonal using a straightedge known to be straight within 5.0 micrometres. A best-fit straight-line approximation is then calculated based on the measured points. The data points are then compared to this straight-line equation and all must fall within ±75 micrometres of the calculated position. This test uses the previously established fact of correct scale across the platen to test the accuracy of one axis against another. Given the previous testing undergone by the subsystems, the likelihood of both axes having errors that offset and allow a bad unit to pass this test is negligible.

These system tests give a high degree of confidence that each 9874A shipped falls well within the specifications shown on the data sheet. As a second confidence check, random units are pulled from the production line at intervals that are statistically determined to give an acceptable confidence level for the sample size. These units are run through a full accuracy test in which the cursor is positioned on the platen at 200 to 300 points using a machine that provides the location with respect to the given origin to within ±5.0 micrometres. The typical machine run through this test is achieving accuracies of ±62.5 micrometres with the worst-case machine achieving ±75 micrometres accuracy. We are thus assured that the production process is repeatably producing machines that provide the user with the specified accuracy.

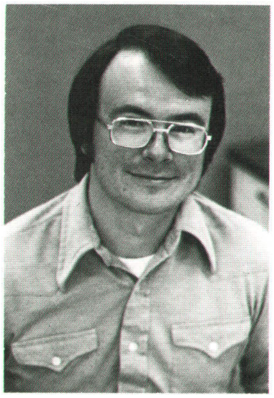
computer on specified conditions, interaction with the display and keypad, and error recognition. This is the same language used by many HP computers, including the 9825A, the 9835A/B, the 9845A, and the HP 1000, and by the 2647A intelligent graphics terminal, to communicate with graphics peripherals. This means that many of the BASIC and HPL language commands included in these machines for graphics are compatible with the 9874A Digitizer. These include commands for scaling to user units, setting windows on the available active area of the digitizer, and the function of digitizing itself.

Inherent Problems of Digitizing

The 9874A Digitizer provides a highly accurate, stable digitizing unit with powerful features to allow the user to solve digitizing problems rapidly. However, there are inherent problems that affect the overall accuracy of the system but are beyond the capability of the digitizer to solve. The first is media compatibility. Since the 9874A Digitizer works on a capacitive technique, materials placed between the cursor and the platen that act to modify the electric field established by the platen traces may cause errors in the position measured by the cursor. These media fall into two categories: conductive media and media with dielectric constant variations. Conductive media can significantly alter the position measured by the cursor, and digitizing of conductive material such as metal sheets will not work. Also included in the category of conductive media are nonconductive materials with moderately conductive surface effects. This category includes paper with graphite pencil markings. These markings can range from high impedance to fairly low impedance, depending upon the hardness of the graphite lead, the width of the line, the length of the line, and the area covered. Tests have shown that a normal-weight line using an H pencil lead can cause up to 250 micrometres of error on the digitized point. This effect is accentuated with the stylus because of its significantly reduced pickup dimensions. We recommend that the stylus not be used with documents drawn with graphite lead pencil. Also in this category is a document with surface conductivity caused by moisture and humidity. Moisture and humidity can cause a significant reduction in the sheet resistivity of the surface of materials such as paper. The complete operating specifications provided in the 9874A manual are designed to take into account typical media conductivity increases in humid environments. If the digitizer is to be used in humid environments these specifications should be closely analyzed to establish the actual operating specifications that will be encountered by the user.

Besides being nonconductive, media being digitized must also have a homogeneous dielectric constant. This is the constant that determines the strength of the electric field at the cursor that results from the drive of one line. In effect, it acts to modify the effective coupling capacitance between the cursor and the line of interest. As we can see from equation 2, if the equivalent coupling capacitances from the various lines are not dependent solely on the distance from the platen line to the cursor, but also depend on the variations of dielectric constant of the media across the platen surface, then the pickup wave will also be affected by this variation, and the positional output may be affected. In normal operation, single sheets of paper or other material are usually well within the bounds of the required homogeneity. However, thick pads of paper or paper with different material on its surface (such as a piece of paper with a strip of adhesive tape on the surface) can cause positional errors of up to 125 micrometres.

Even more significant than the electrical properties of the material are limitations imposed by the document material, which can range from paper to mylar to 35-mm slides. Documents all have one general characteristic: they are sensitive to variations in temperature, humidity, and aging. In fact, this sensitivity may not be homogeneous over the surface of the material, especially in cases where a specific grain direction exists. Variations of this type can range up to several percent for certain types of paper. Thus a variation of over 1.25 mm can be seen for slight variations around standard room temperature and humidity. Another significant effect is dimensional variations caused by bending or folding of the source document. Even for mylar, the variation from a 90° bend of small radius (2.5 mm or less) can be as much as 100 to 150 micrometres.

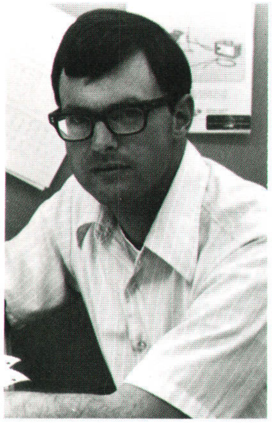


Lawrence E. Brown

Born in Albany, New York, Larry Brown received his BSME degree in 1968 and MSME degree in 1971 from Rensselaer Polytechnic Institute. After graduation, he worked as an emissions test engineer for an automobile manufacturer and did a year of postgraduate work at Rensselaer before coming to HP in 1973. As lead engineer for the product design of the 9874A Digitizer, Larry was responsible for its platen and platen process design. He also designed the four-pen "stable" mechanism concept for the 9872A Plotter. A real downhill and crosscountry skiing enthusiast, Larry has a patent on a ski and pole carrier and for eight years was a semipro ski instructor in Vermont. When not "schussing the slopes," he enjoys hiking, camping and remodeling his home. The Brown family—Larry, his wife, three cats and two dogs—lives in Loveland, Colorado.

Acknowledgements

I would like to thank all of the members of the project team who contributed to make the 9874A the product it is. Worthy of particular note are: Geoff Chance, who was the project manager during the initial definition phase of the project, Alan Richards, who took over as project manager following Geoff's promotion and guided us into production, Larry Brown, who was responsible for the platen process and was project leader on the mechanical side, Jerry Nichol, who did the overall mechanical design, Bill Dalebout, our industrial designer, Henry Hetzel, who was responsible for the cursor design, Mike Tremblay, who wrote all of the software for the internal processor, Mark Trasko, who designed the processor and interface electronics, Dave Chamness, who did the preliminary design of the stylus, Tony Mallon, who provided valuable help in the testing and EMI design, Paul Bonomo, who set up the manufacturing processes to build the unique parts of the unit, and finally Dave Kinsell, who came in toward the end of the project and helped solve the usual problems that threaten to hold up the final release.



Henry T. Hetzel

Responsible for the design of the cursor and vacuum system for the 9874A Digitizer, Henry Hetzel received his BS degree in physics from Haverford College in 1961 and MSEE degree from Colorado State University in 1970. Henry has been an HP employee since 1965 and is named inventor on three patents relating to the 9874A Digitizer. He also helped design the 11100 Series Transfer Standard Resistors, and did thermal printhead analysis for the 9800 Series Desktop Computers. Before coming to HP, he was self-employed, converting old mechanical adding machines to instruments that could be used by the blind. Henry lives on a farm in Loveland, Colorado, and spends much of his leisure time riding and caring for his two horses.

Frank P. Carau

A 1971 BSEE graduate from Virginia Polytechnic Institute and State University, Frank Carau was lead engineer for the electronic design of the 9874A Digitizer, and was responsible for its drive technique, keypad, display, beeper and power supply design. Prior to working on the 9874A, Frank did the preliminary work on the processor design for the 9872A Plotter, and he is now project manager in HP's Desktop Computer Division peripherals lab. Born in Washington, D.C., Frank worked as an electronics engineer with the federal government after graduation until he joined HP in 1974. He is a member of IEEE and is named inventor on a patent on the 9874A digitizing technique. A resident of Loveland, Colorado, Frank is married, has two children (ages eight and four) and is expecting his third child in March. Camping, hiking, jogging, reading, photography, skiing and church activities keep Frank busy during his off hours.

SPECIFICATIONS

HP Model 9874A Digitizer

Instruction Set

An easy-to-use, two-letter mnemonic graphics language drives the 9874A. The interface code is given to the 9874A through the HP-IB interface card. Following is a listing of the commands.

DIGITIZE MODES

SG - Sets the Single Sample Mode
CN - Sets the Continuous Mode
OD - Output Digitized Point
OC - Output Current Cursor Position
OA - Output Actual Cursor Position
RC - Read Cursor Position
ON - Output Annotation
AA - Sets the Axis Align Mode
AE - Sets the Axis Extend Mode
PO - Sets Point One Mode
PT - Sets Point Two Mode
IP - Input Scaling Points (P_1, P_2)
OP - Output Scaling Points (P_1, P_2)
WO - Sets Window One Mode
WT - Sets Window Two Mode
IW - Input the Window Coordinates
OW - Output the Window Coordinates

DIGITIZE SWITCH MODES

SN - Switch Normal
SF - Switch Follow
TP - Take Point

AIR SWITCH MODE

AN - Sets the Air Normal Mode
AT - Sets Air Toggle Mode
AV - Activate Vacuum
RV - Remove Vacuum

SPECIAL FUNCTION KEYS

SK - Set Special Function Key
OK - Output Special Function Key

ADDITIONAL COMMANDS

BP - Variable Frequency Beep
DD - Display Driver
LB - Label the Display
OR - Output Resolution
OI - Output Identification
OF - Output Factor
CC - Compatibility Command
TD - Digitizer Self-Test

CONFIGURATION STATUS

DF - Default
DC - Digitizer Clear
IN - Initialize
OS - Output Status
OE - Output Error
IM - Input Masks

COMPUTER REQUIREMENTS

Computer/Controller	9815A Opt. 002	9825A	9830A/B	9835A/B	9845A/S	HP 1000	2647A
ROMs or software	Built-in	Gen. I/O 98212A	Ext. I/O 11272B/F	I/O 98332A	I/O 98432A	RTE-M/IV 92840A	BASIC Subroutine
HP-IB Interface (IEEE Std 488-1975)	98135A	98034A	59405A	98034A	98034A	59310B	13296A

Specifications

RESOLUTION: 0.025 mm (.000984 in).

ACCURACY

CURSOR: ±0.125 mm (.00492 in) from 10°C to 40°C.
±0.200 mm (.00787 in) from 0°C to 55°C.
STYLUS: ±0.500 mm (.01969 in) from 10°C to 40°C
±0.600 mm (.02362 in) from 0°C to 55°C.
ACTIVE DIGITIZING AREA: 435 mm × 315 mm (17.13 in × 12.40 in).
AXIS EXTENSION (EITHER AXIS): ±53.69 km (±33.36 miles).
CURSOR/STYLUS DOCUMENT THICKNESS: full accuracy maintained digitizing through 4 mm (0.1575 in) thick paper.
DOCUMENT MATERIAL: nonconductive.

COORDINATE SYSTEM: Absolute; reference system is unaffected if cursor is removed.

POWER REQUIREMENTS

SOURCE (+5%, −10%)(switch selectable): 100V/120V/220V/240V.
FREQUENCY: 48 Hz to 66 Hz.
CONSUMPTION: 1.75A @ 100V, 1.43 A @ 120V, 760 mA @ 220V, 730 mA @ 240V.

SIZE/WEIGHT

HEIGHT
PLATEN LOWERED: 203.2 mm (8.00 in)
PLATEN EXTENDED: 546.1 mm (21.50 in)
WIDTH: 850.9 mm (33.50 in)
DEPTH: 520.7 mm (20.50 in)
WEIGHT: 27.4 kg (60.5 lb)

PRICE IN U.S.A.: $6200.

MANUFACTURING DIVISION: DESKTOP COMPUTER DIVISION
3400 E. Harmony Road
Fort Collins, Colorado 80521 U.S.A.

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Sept.	1978	HP-GL graphics language	—
July	1978	HP-IB interface chip (PHI)	—
July	1978	HP-MCL, measurement and control language	2240A
Oct.	1977	Histogram measurements	5420A

I

Oct.	1977	Interest calculations	HP-92
May	1978	Interface, computer to CRT	1350A
Sept.	1977	Interference caused by electrosurgery	78333A
Oct.	1977	Internal rate of return (IRR)	HP-92
Nov.	1977	Inverse trig-function algorithms	—

J

K

L

July	1978	Laboratory automation	2240A
Sept.	1977	Language, graphics (HP-GL)	—
Sept.	1978	Language, graphics (HP-GL)	—
July	1978	Language, measurement and control (HP-MCL)	2240A
Oct.	1978	Large program capability, RTE-IV	92067A
Dec.	1977	LCR meter, automatic wide-range	4262A
Feb.	1978	Logic state analyzers	—
Sept.	1978	Long-axis plotter	7245A
Oct.	1977	Low-frequency signal analysis	5420A
Sept.	1978	Low-frequency signal analysis	3582A
Nov.	1977	LSI circuits, NMOS II	—

M

July	1978	Measurement and control language (HP-MCL)	2240A
July	1978	Measurement and control processor	2240A
Oct.	1978	Memory systems	HP 1000 F-Series
Nov.	1977	Microprocessor, NMOS II	—
Aug.	1978	Microprocessor prototyping system	—
Sept.	1977	Microstep control system	7221A 9872A
May	1978	Microwave counter	5342A
Nov.	1977	Microwave signal generator	8672A
Sept.	1977	Multicolor X-Y plotters	7221A 9872A
Dec.	1978	Multimeter, 4½-digit, logging	3467A
Oct.	1978	Multipoint terminals for HP 1000 computer systems	12790A
Oct.	1978	Mother partitions, in RTE-IV	92067A

N

Mar.	1978	Networks, computer	—
Nov.	1977	NMOS II LSI circuits	—

O

Oct.	1978	Operating system, RTE-IV, for HP 1000 systems	92067A
Aug.	1978	Oscillator, triggered phase-locked	—
Dec.	1977	Oscilloscope, delta-time with counter	1743A

P

Sept.	1978	Paper drive, bidirectional	7245A
Sept.	1977	Patient monitoring, hostile environment	78333A
Aug.	1978	Period generator	5359A
Aug.	1978	Period measurements	5370A
July	1978	PHI (HP-IB interface chip)	—
Sept.	1978	Plotter/printer	7245A
Sept.	1977	Plotters, X-Y, four-color	7221A 9872A
Nov.	1978	Printer, 400 lines per minute, dot-matrix	2608A
Nov.	1978	Printer, 180 characters per second, dot-matrix	2631A/G
Sept.	1978	Printer/plotter	7245A
Apr.	1978	Printer, thermal, for 9845A	9845A
Nov.	1978	Printing terminal	2635A/39A
Sept.	1978	Printhead, thin-film thermal	7245A
July	1978	Process control	2240A
Mar.	1978	Program-to-program communication	HP 1000 HP 3000 2026
Mar.	1978	Project Prelude	—
Nov.	1977	Pulse modulator, microwave	11720A
Aug.	1978	Pulse width and delay generator	5359A

Q

R

Jan.	1978	Raster scan graphics	2648A
Apr.	1978	Raster scan graphics	9845A
July	1978	Reader, card, multifunction	3070B
Oct.	1978	Real-time executive system (RTE-IV)	92067A
Sept.	1977	Recorders, X-Y, four color	7221A 9872A
Mar.	1978	Remote command processing	HP 1000 HP 3000
Mar.	1978	Remote data base access	HP 3000
Mar.	1978	Remote file access	HP 1000 HP 3000
Mar.	1978	Remote job entry	2026

S

Sept.	1977	Safety problems in battery-powered medical instruments	78333A

Part 2: Subject Index (continued)

PART 3: Model Number Index

PART 4: Author Index

1-mHz-to-50-MHz Signal Source Combines Synthesizer Accuracy, Multimode Operation, and Easy Programming

Offering features not previously available in a single instrument, this new programmable signal source provides many kinds of test stimuli for either automatic or bench test applications.

by Tilman Schad, Dieter Kible, and Peter Brünner

SOFTWARE AND HARDWARE COSTS of automatic and bench testing can be reduced if a single source can provide all the stimuli required to test any given device. While no such universal source yet exists, the new Model 8165A Programmable Signal Source (Fig. 1) is a step in that direction, having most of the capabilities needed for the majority of today's automatic, semiautomatic, and manual test setups.

The new source offers an extensive catalog of features not previously combined in a single instrument. Helpful in testing logic families such as TTL and MOS are its fast-transition pulses, variable offset and amplitude, and dc capability for threshold testing. For linear circuit testing, the 8165A has logarithmic sweep, FM and AM, and sine, ramp and square waveforms. It also has a single-shot trigger for response time measurements, and a counted burst capability for clocking digital circuits to a particular state. The accuracy of manual and programmed settings is such that no external equipment or setup loops are required.

To simplify software requirements for both system integration and daily operation, the 8165A offers full programmability of all modes and parameters, identical syntax for front-panel and remote operation, handy mnemonics reproduced on a logically arranged front panel, and detailed diagnostic information for debugging in the event of a program error. Operating parameters can be transferred from the source to the system controller so the controller can learn manual settings made to establish critical values. Further, to save system controller memory, the source itself can store ten complete sets of operating modes and parameters, so a new operating state can be brought into effect by a single program statement. This also saves time in bench applications because entire operating states can be recalled by two front-panel keystrokes. Built-in batteries maintain data storage when the instrument is turned off.

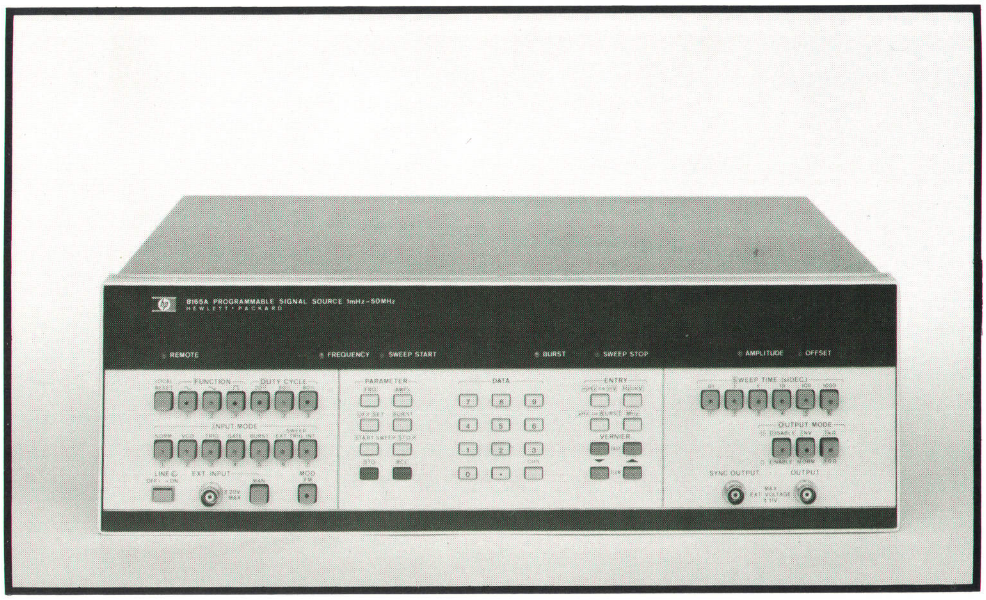

Fig. 1. *Model 8165A Programmable Signal Source produces sine, triangle, and square waves in a frequency range of 1 mHz to 50 MHz. It also generates pulses or ramps with 20% or 80% duty cycles in a range of 1 mHz to 19.99 MHz. For stability, the output is phase-locked to a quartz crystal oscillator. HP-IB input/output is standard. An option provides logarithmic sweep and AM.*

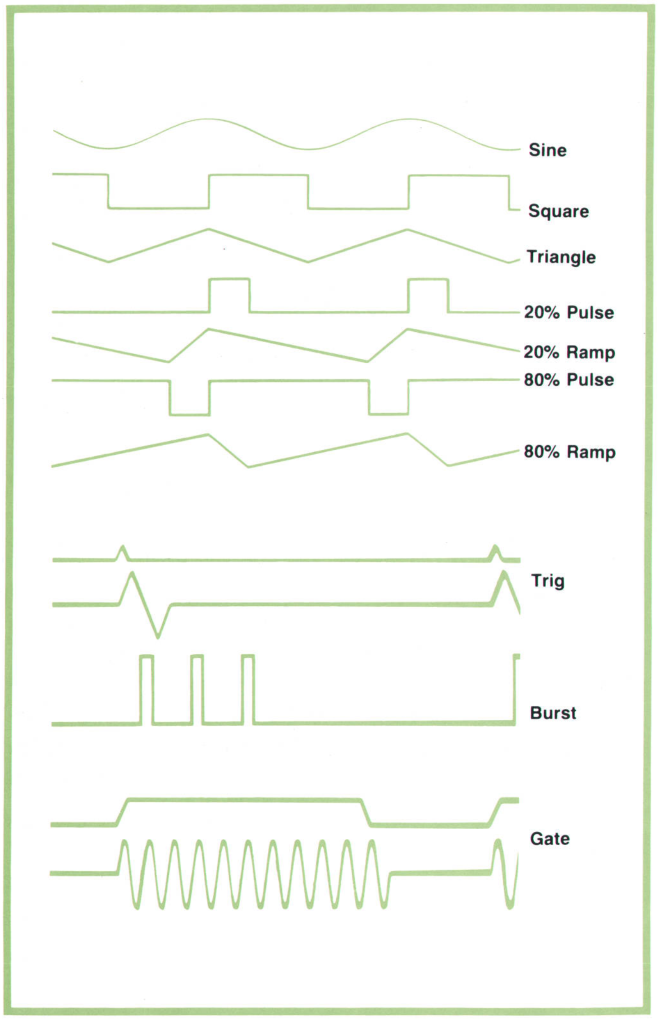

Fig. 2. *Typical 8165A output waveforms.*

Sine, triangle and square waves are generated in the frequency range from 1 millihertz to 50 megahertz. Sweep is available as an option. Pulses or ramps with 20% to 80% duty cycles are generated in the range from 1 millihertz to 19.99 megahertz. Pulse transition times are less than 5 nanoseconds. Source impedance can be set to 50 or 1000 ohms.

A precision 10-MHz quartz crystal oscillator is used as a frequency reference. Phase locking to the reference achieves output frequency stability of $\pm1\times10^{-5}$ of the programmed value. Frequency resolution is four digits, which provides a resolution of 1 microhertz in the 1-9.999 millihertz range.

Fig. 2 shows various types of 8165A output waveforms.

Design Philosphy

Some challenging engineering problems had to be solved to make the 8165A a reality. One major problem is that, with a frequency range of more than ten decades, amplifier circuits must be designed without ALC loops to keep the settling time short. This requires exceptional gain and dc stability in all circuits. Also, high-speed amplifiers are mandatory to achieve output signals with transition times faster than 5 ns.

Another problem stems from the fundamental difference between conventional and fully programmable instruments. In bench instruments, dial settings are stored by the dials and pushbuttons themselves, and can be checked and changed even when switched off. To provide a similar feature in a fully programmable instrument, the settings must be stored and rechecked automatically without enabling the output. So that power interrupt does not mean that the instrument must be reprogrammed, a non-volatile memory for the operating parameters must be included. An added advantage of the 8165A is that no measuring instruments are necessary to verify the microprocessor-controlled parameters.

To meet these and other requirements the design concept is as shown in the block diagram, Fig. 3. A 1-kHz-to-50-MHz oscillator (HF VCO in Fig. 3) generates a triangle output that may be used directly or fed to a sine shaper. The square wave is derived from the HF VCO's current switch drive voltage. Changing from triangle to ramp form, and consequently changing the square wave duty cycle, is achieved by varying the charge and discharge rates of the HF VCO's ramp capacitor. Duty cycles and ramp symmetries of 20%, 50%, and 80% are available. For high stability in continuous operation, the HF VCO can be phase-locked to an internal or external 10-MHz frequency reference.

Signals below 1 kHz are generated by a low-frequency generator (LFG). Simplified, it consists of an up-down counter (to divide the frequency) followed by a digital-to-analog converter (to synthesize a triangle). The counter is clocked by the HF VCO at a frequency 10,000 times higher than the output frequency of the D/A converter. This allows the HF VCO to run continuously in the phase-lock mode even when a triggered low-frequency signal is required. Consequently, the basic crystal accuracy and stability of the output are preserved in all operating modes.

Microprocessor Control System

To control a multi-capability, flexible instrument like the 8165A, such a vast amount of data has to be processed that a microprocessor is essential. Typical tasks handled by the 8165A's microprocessor are manual data entry via the keyboard, preparation of data to set up the generating circuits, data checking, data reporting, and remote data entry via the HP-IB.* Data is stored by the microprocessor so that information about operating states or errors can be recalled or sent over the HP-IB.

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*The Hewlett-Packard Interface Bus is HP's implementation of IEEE Standard 488 and identical ANSI standard MC1.1.

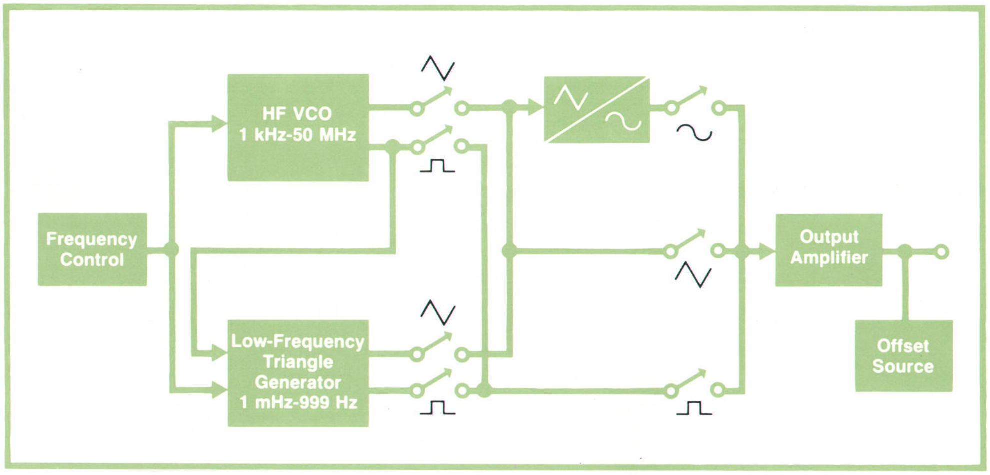


Fig. 3. *8165A basic block diagram. For frequencies above 1 kHz the HF VCO generates a triangle output that is either used directly or fed to a sine shaper. For output frequencies below 1 kHz, the low-frequency generator divides the HF VCO output frequency. The operation of each block is controlled by a microprocessor (not shown).*

Communication from the microprocessor to the analog circuits is conducted over an internal bus that works into an acceptor for each controlled analog circuit. Fig. 4 shows the microprocessor bus structure. The acceptor has the function of storing just the information intended for its particular analog circuit, and to do this, each acceptor has a unique address.

The internal bus consists of 16 data/address lines and three handshake lines. The handshake lines define whether data or an address is being transmitted and coordinate the information transfer. The HDAT (high data) line is high when data is transmitted and low when an address is transmitted. The NDDV (device data valid) line provides a positive transition to signify that the data or address on the bus is valid. The HINH (high inhibit) line goes high to terminate a transmission.

A typical acceptor consists of a latch and a latch-enabling circuit, the latter reacting when the appropriate address appears on the bus. There are seven different addresses for the seven functions: frequency, input mode, waveform, burst count, amplitude, offset, and sweep start-stop frequencies. Circuit configuration and timing of a typical acceptor

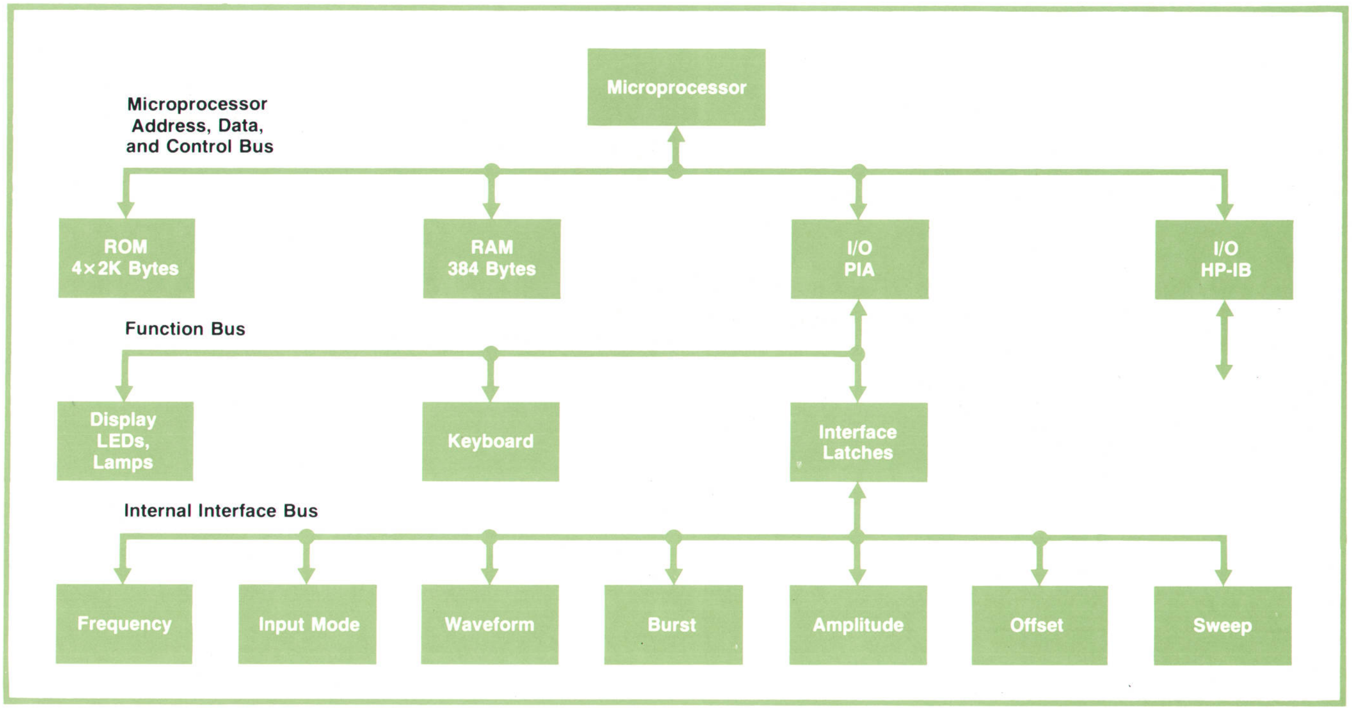


Fig. 4. *8165A microprocessor bus structure. To control the instrument's seven functions, the microprocessor communicates by means of a peripheral interface adapter (PIA) and an internal bus. The bus, consisting of 16 data/address lines and three handshake lines, works into seven acceptor circuits, one for each controlled analog circuit.*

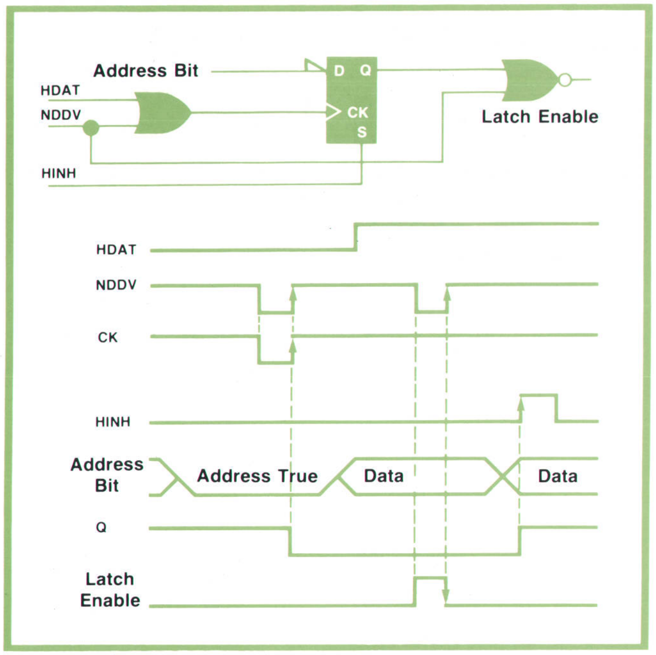


Fig. 5. *Typical acceptor circuit consists of a latch and a latch enable circuit, the latter shown here. When the appropriate address line of the internal bus goes low, the latch enable signal is generated, allowing data to be clocked from the bus into the corresponding latch.*

are shown in Fig. 5.

The flip-flop, normally with Q high, is clocked by NDDV when HDAT is low. If the latch's address bit is active (low), Q will then go low and permit the next NDDV pulse to enable the latch. When the data is terminated, the HINH pulse returns the flip-flop to its normal state. Data transmitted over the line used by the address bit has no effect on the flip-flop when HDAT is high. If the data for the acceptor consists of more than one 16-bit word, the words are transmitted serially and stored in a corresponding number of latches. Separate enable signals for each latch are generated by a master/slave flip-flop arrangement. Some acceptors in the 8165A use two address bits: in these cases the appropriate lines are applied to an OR gate to supply the flip-flop's D input.

The M6800 microprocessor with 4×2K-byte read-only-memory (ROM) and 384-byte CMOS read/write random-access memory (RAM) controls the input/output section including the HP-IB interface. One M6820 PIA (peripheral interface adapter) performs interfacing between the microprocessor bus and the peripherals, which include the display, the keyboard, and the interface latches.

Operating the 8165A

A disadvantage of many digital instruments is volatility of data after a power interrupt. The 8165A's CMOS RAMs with battery backup are able to store the data approximately four weeks. When the instrument is switched on, the output is automatically disabled to prevent possible damage to a device under test. A complete error test is also performed. Ten registers are provided to store ten complete operating states. This is very convenient on the bench as well as for systems applications, when rapid and repetitive changes of parameters are required.

An important design goal was to give the user maximum flexibility in setting up. Data loading is simple: select the parameter, and enter the value followed by a delimiting unit key. Simple task pushbuttons (e.g., waveform, input mode) may be pressed at any time during programming. A complete error test is performed after the change of any parameter. The error routine starts by verifying overrange or underrange of entered data. It continues by testing the compatibility of existing data with data just entered. After this sequence, data is stored and processed and the instrument updated.

If an error occurs, the keyboard is locked so the only keys that will operate are those that allow the elimination of the error. As shown in Fig. 6, the keyboard, organized as an 8×9 matrix, is scanned serially by the processor. One-half of the PIA, in conjunction with a multiplexer and a demultiplexer, is responsible for the keyboard matrix. When a changing key status is recognized, key bounce effects are eliminated by reading the status again after a few milliseconds. If there is no further change, the new status is accepted by the control system.

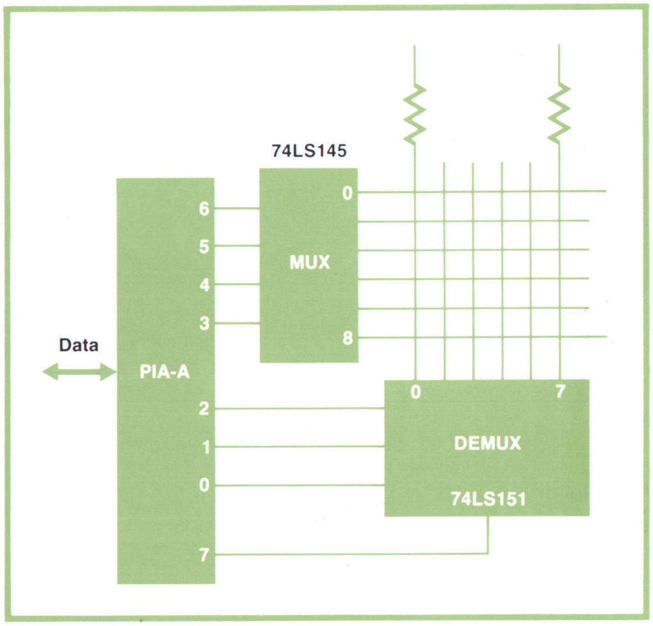


Fig. 6. *The keyboard is organized as an 8×9 matrix and is scanned serially by the processor. Half of the PIA, a multiplexer, and a demultiplexer form the microprocessor/keyboard interface.*

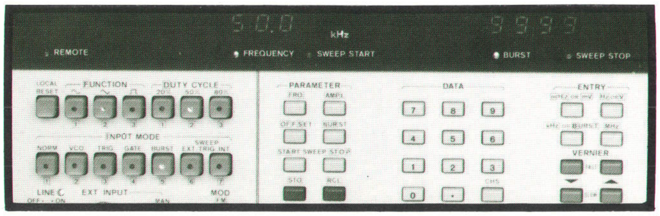


Fig. 7. *Mnemonics, indicated on the front panel by framed letters, specify the HP-IB commands necessary to program the corresponding functions.*

HP Interface Bus

Remote programming is via the HP-IB and uses the same strategy as manual data entry. Two PIAs and some additional logic perform interfacing between the HP-IB and the 8165A. HP-IB service is controlled by the microprocessor. For example, it interprets universal and addressed commands, and supervises handshake and data reception. To simplify data handling, the interface system operates on an interrupt basis.

Mnemonics, indicated on the front panel by framed letters, specify the system controller keystrokes necessary to program the corresponding functions via the HP-IB (see Fig. 7). For example: "I1 F1 FRQ 1.23 MHz" sets the 8165A to normal mode, sine waveform, and a frequency of 1.23 MHz. For better readability of a written program, blanks and commas can be used in any number within the command strings. They are ignored by the 8165A.

As talker on the HP-IB, the 8165A is able to transmit a complete set of data on request, including its current operating modes and parameter settings. Thus the system controller can learn manual settings. The set of data consists of eight-character strings, ASCII coded, with a maximum of 16 characters per string. Each string is terminated by a carriage-return/line-feed. Data is received by the 8165A using the same syntax as for sending.

Frequency Generation 1 kHz to 50 MHz

The 8165A uses a phase-locked loop (PLL) method of indirect frequency synthesis that gives the advantage of transferring the accuracy and stability of a crystal source to the variable-frequency output. In a basic PLL frequency synthesizer, a voltage-controlled oscillator (VCO) is tuned roughly to the required frequency by a tuning voltage. A known portion of the output signal is compared with a stable reference frequency, and any phase difference appears as a voltage at the output of the phase detector. This signal is smoothed and applied to the VCO to correct the output frequency. Variable frequencies are generated by inserting a programmable ÷N divider between the VCO output and the phase detector.

The 8165A uses two other loops in addition to the main reference loop (Fig. 8). This reduces settling time by keeping the division factor smaller and loop reference frequencies higher. These extra loops effectively provide the ÷N function. The output frequency, f_{out}, is divided by a factor R so that the main reference loop operates only in the frequency range 1-10 kHz; this also contributes to short settling times.

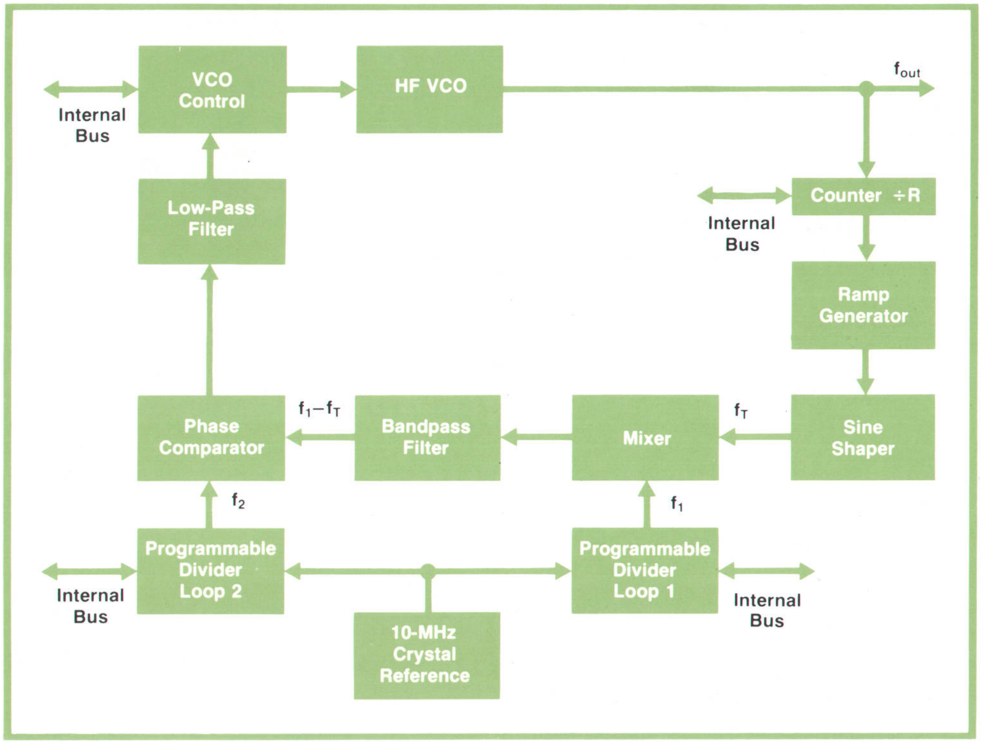


Fig. 8. *Phase-locked loop method of indirect frequency synthesis is used in the 8165A. Two divider loops (shown here as single boxes) in addition to the main loop help keep the main loop division factor smaller and loop reference frequencies higher. The main loop operates in a range of only 1-10 kHz; this helps shorten the settling time.*

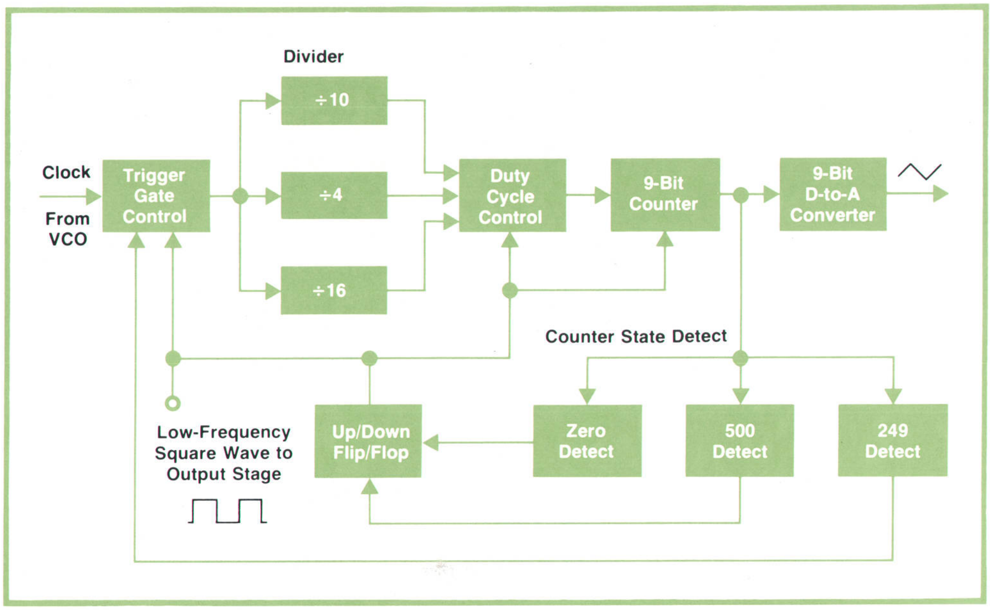


Fig. 9. *Low-frequency generator (LFG) divides the HF VCO output frequency to generate output frequencies below 1 kHz. The division factor ranges from 10^4 to 10^6. Because the LFG runs continuously, crystal accuracy is retained for the triggered and gated modes as well as for the normal mode.*

The divide-by-R counter output is applied to a ramp generator and a sine shaper to provide a sine wave that is mixed with the output of the first loop. Use of a sine wave instead of a square wave or ramp helps keep spurious products of the mixer small. These products can cause low-frequency jitter.

The difference frequency is filtered from the mixer output and compared with the second loop's frequency. If f_{out} is accurate and the phase detector output is zero, then

$$f_1 - f_t = f_2,$$

and hence

$$f_{out} = R \times f_t = R \times (f_1 - f_2)$$

This means narrow tuning ranges for f_2 (900-801 Hz) and f_1 (1.9-10.8 kHz). At frequencies above 1 kHz, the PLL is disabled in gate, trigger, and burst modes. In normal mode above 1 kHz, the PLL is enabled and the control voltage to the main VCO is modified by the modulating signal so that the deviation is constant as a percentage of the output frequency.

Frequency Generation below 1 kHz

Frequencies below 1 kHz are obtained by dividing the output of the main VCO (see Fig. 9). The VCO clocks an up/down counter whose count direction is determined by a flip-flop. At counter states of 0 and 500, the flip-flop changes its status and reverses the count direction. The parallel counter outputs are applied to a nine-bit digital-to-analog converter, which generates an approximation to a triangle wave consisting of 1000 discrete voltage levels, or steps, per cycle.

In trigger, gate, or burst mode, counter state 249, which represents the baseline, is detected for gating, synchronization, and cycle counting. For symmetrical waveforms, the duty cycle control divides the clock by a factor of 10. In the 20/80 mode the division factor is four for the shorter flank and 16 for the longer, the period remaining constant. In the low-frequency range from 1 mHz to 999.9 Hz the 8165A's phase-locked HF VCO runs at frequencies 10^4 to 10^6 times higher than the output of the low-frequency generator. This guarantees high accuracy in the low-frequency output. Because the low-frequency generator runs continuously, crystal accuracy is retained for the triggered and gated modes as well as for the normal mode.

HF VCO

The HF VCO generates a triangular voltage in the range 1 kHz to 50 MHz by charging and discharging a capacitor at a constant rate (see Fig. 10). This is done using a switchable positive current source, I_x, and a smaller negative current source, I_y. When the positive current source is on, the capacitor charges at $I_x - I_y$. When the positive current source is off, the capacitor discharges at I_y. The positive source is switched by a pair of transistors controlled by a Schmitt trigger driven from the ramp voltage.

Frequency is determined by the time taken for the ramp voltage to reach the Schmitt trigger thresholds. Consequently, it is dependent on the ramp capacitor value and the charge and discharge currents. These are varied according to the frequency range and the selected output frequency. Symmetry depends on the ratio of charging current $(I_x - I_y)$ to discharging current (I_y). In the range 1 kHz to 19.99 MHz, symmetry is selectable (20%, 50 %, 80%). At 20 MHz and above it is fixed at 50%.

One of the main problems in generating a clean triangle with this technique at high frequencies is caused by the parasitic inductance (L) and resistance

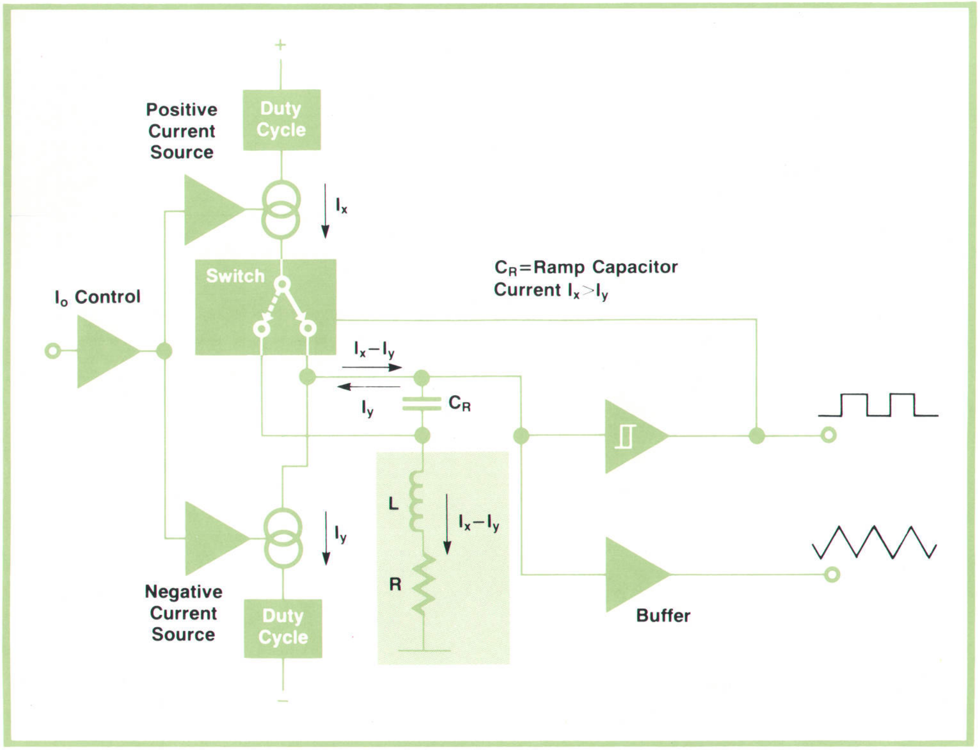


Fig. 10. *The HF VCO (voltage-controlled oscillator) generates a triangular voltage in the range 1 kHz to 50 MHz by charging and discharging a capacitor at a constant rate determined by two current sources. A switching arrangement compensates for the effects of stray inductance (L) and resistance (R).*

(R) of the ramp capacitor and the range switching circuitry. If L and R are not equal to zero, a spike and a step, respectively, occur on the triangle at the switching point. To compensate for this, a virtual ground is generated by switching the current I_x to either end of the appropriate ramp capacitor directly via an additional switching circuit. For the same reason the ramp capacitor for the highest frequency range is printed directly on the circuit board.

Function and Pulse Generation

In sine operation, a triangle waveform from the VCO or LFG goes to a sine shaper, the sine amplifier, the buffer, and the output driver. Sine shapers in function generators usually consist of a set of diodes. These are connected to voltage sources with defined source resistance and are fed by a source with defined resistance. Although these shapers are valuable in the frequency range up to 10 MHz, even the use of diodes with very low storage times cannot increase the frequency range significantly. The sine shaper concept used in the 8165A, therefore, is different The basic cell is shown in Fig. 11. It consists of a differential amplifier whose gain is determined only by the resistors R_N. The breakpoints are determined by the current I_N. The shaper circuit consists of five cells connected in parallel (i.e., N = 1,2,3,4,5). An advantage of this approach is that the gain is determined by resistors and is therefore independent of temperature variations. However, the input amplitude and offset must be very stable, since an amplitude drift would cause odd harmonic generation, and an offset drift would cause even harmonic generation. In triggered mode an offset drift cannot be compensated. At high frequencies and continuous waveforms, automatic compensation is switched on.

The pulse waveform is converted from the ramp by means of a Schmitt trigger. To obtain a pulse with a zero-volt baseline, an offset is added to the pulse amplifier output. For frequencies above 1 kHz, the VCO ramp is switched to the output driver directly.

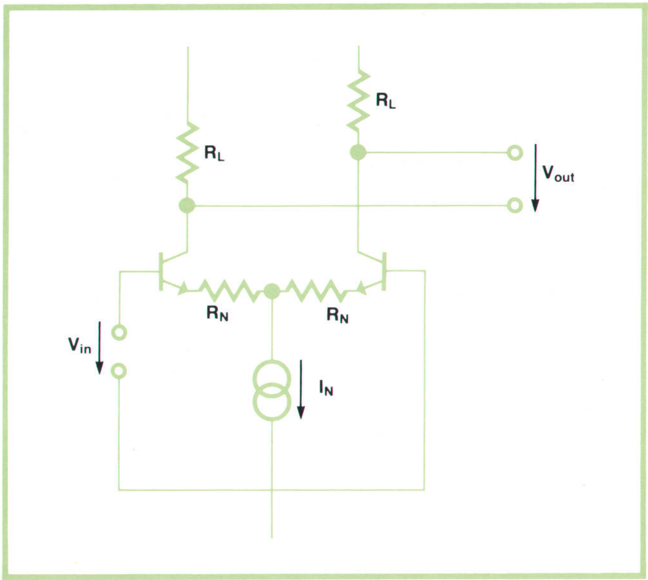


Fig. 11. *Sine shaper consists of five of these basic cells connected in parallel. Gain is determined by resistors and is independent of temperature variations.*

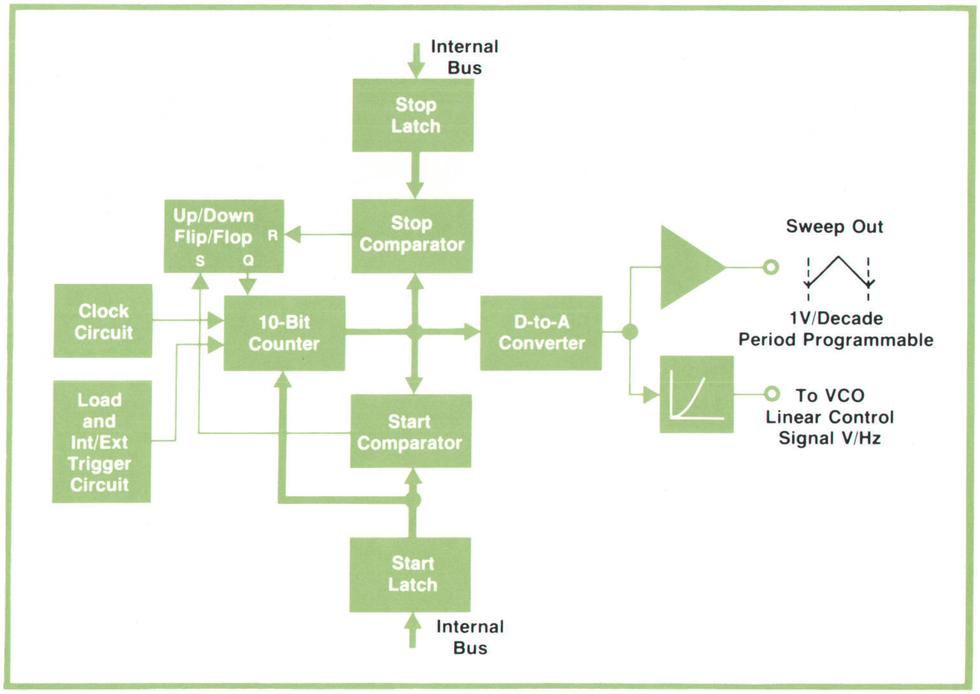


Fig. 12. *Optional logarithmic sweep generator is based on an up/down counter and a digital-to-analog converter. Sweep can cover up to three decades.*

For lower frequencies, the ramp waveforms from the low-frequency generator are provided to the output driver.

Counted Burst Capability

The 8165A has a counted burst capability, which means that, after a trigger signal is applied, a preprogrammed number of cycles are generated. The technical problem of designing a high-speed programmable counter with common ECL and TTL technology is solved in the usual way: A programmable up-counter is preset to a number $Y-(N-1)$, where Y is the upper limit of the counter and N is the required number of output cycles. The counter is monitored, and when the state Y is detected, the next output cycle of the HF or LF oscillator is stopped. The value of $N=1$ is treated as a one-shot trigger, as in external trigger mode, and the value $N=0$ disables the trigger input and allows the 8165A to be used as a dc source (signal off, offset variable). Thus the full range of 0 to 9999 cycles per burst is available.

Optional Sweep/AM

Option 002 provides the 8165A with logarithmic sweep and amplitude modulation capabilities.

Logarithmic sweep output allows the user to sweep logarithmically between two frequencies as an alternative to the linear sweep available in the VCO mode. A range of three decades can be covered. Unlike some sweep circuits, a triangle instead of a sawtooth is generated. The advantage of this waveform is that there is no need for a blanking stage in an oscilloscope or for a pen lift circuit in an X-Y recorder. The sweep generator is based on an up/down counter and a digital-to-analog converter (see Fig. 12).

After the start frequency has been entered, the stop frequency is checked against the total available sweep range. Following this, the logarithm of the start frequency is automatically stored by the start latch and is subsequently loaded into the 10-bit counter. After the external trigger, the counter accumulates the pulses generated by the clock generator until the stop frequency has been reached. The flip-flop then reverses the counter. The counter's output is converted to a triangular waveform by a 10-bit digital-to-analog converter (DAC). The DAC's output is converted by an antilog amplifier to produce a voltage for controlling the HF VCO. A signal for external deflection purposes (1V per swept decade) is made available by buffering the DAC's output.

Besides sweep, 8165A Option 002 also provides amplitude modulation. The standard instrument has an FM mode, and PCM can be carried out in the gate mode. Because there are no restrictions on selecting the input mode in conjunction with AM, complex waveforms can be generated. Amplitude modulation indexes between 0 and 100% are possible, independent of the programmed amplitude.

The AM stage is based on an electronic attenuator IC, similar to those used in the 8082A 250-MHz Pulse Generator.[1] In this application two basic cells are connected in parallel. The contribution of this arrangement is that the envelope distortion of the modulator is better than −60 dB for frequencies up to 1 MHz.

Acknowledgments

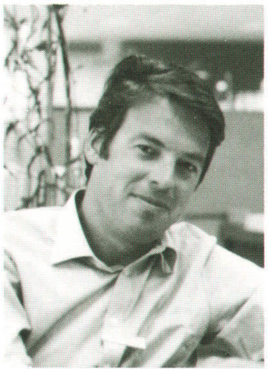
For their very significant contributions, we'd like to thank: Georg Heier for the design of the HF VCO and

the output amplifier; Werner Stahel for the LF Generator; Wolfgang Kappler and Sigurt Krass for the design of the microprocessor system and software architecture; and Rainer Eggert for the mechanical design. Special thanks, too, for the encouragement and help we received from Reinhard Falke, R&D section manager, and Jörn Kos, engineering lab manager.

Reference

1. G. Globas, J. Zellmer, and E. Cornish, "A 250-MHz Pulse Generator with Transition Times Variable to Less than 1 ns," Hewlett-Packard Journal, September 1974.

Tilman Schad



Tilman Schad joined HP GmbH in 1974 as an R&D engineer on the 8165A. He eventually became project leader of the 8165A and then section leader. Tilman is now manufacturing manager of the Böblingen Instrument Division. He holds a Dr. Ing. degree in electrical engineering from the Technische Universität Stuttgart. Living in Stuttgart with his wife and two-year old son, he spends much of his spare time as an amateur radio operator.

Dieter Kible

Dieter Kible joined HP GmbH in 1975 as an R&D engineer at Böblingen Instrument Division. Initially he worked on hardware modules for the 8165A, and later became responsible for the microprocessor control (hardware and software development) and the HP-IB interfacing of the 8165A. He earned his Diplom Ingenieur from the Technische Universität Stuttgart in 1975. Dieter is married and enjoys photography and personal computing.

Peter Brünner

Born and raised near the Alps, Peter Brünner earned his Diplom Ingenieur at the Technische Universität Stuttgart in 1976, joined HP GmbH, Böblingen Instrument Division the same year and started on the 8165A Programmable Signal Source. He contributed the LFG, offset, burst counter and AM/sweep option. Peter is a member of the HP chess team, and enjoys swimming and skiing. He and his wife are expecting their second child soon.

SPECIFICATIONS

HP Model 8165A Programmable Signal Source

OUTPUT WAVEFORMS: Sine, square, pulse, triangle, ramp.

FREQUENCY CHARACTERISTICS

RANGE: 0.001 Hz to 50.00 MHz (0.001 Hz to 19.99 MHz for 20 and 80% duty cycle/symmetry).

ACCURACY, STABILITY AND RESOLUTION:

	Norm	Trig, Gate, Burst	
		f<1 kHz	f≥1 kHz
Accuracy	0.001%*	0.001%*	5%
Stability over 1 hour	$\pm1\times10^{-6*}$	$\pm1\times10^{-6*}$	$\pm5\times10^{-4**}$
Stability over 24 hours	$\pm1\times10^{-6*}$	$\pm1\times10^{-6*}$	$\pm1\times10^{-3**}$
Resolution (digits)	4	4	3

* Accuracy and stability can be improved by phase locking to an external frequency reference.

** After 15 minutes

JITTER: ≤0.2% at 20/80% duty cycle/symmetry,
≤0.1% (≥1 kHz),
≤0.02% (0.1 Hz - 999 Hz), further improvement at lower frequencies.

Output Characteristics

(50Ω Source terminated by 50Ω load unless stated otherwise)

RANGE: amplitude and offset independently variable within ±10V.

SOURCE IMPEDANCE: selectable 50Ω ± 1% or 1 kΩ ± 10%, in parallel with 50 pF.

AMPLITUDE: 10.0 mV pp to 10.0V pp,
2.00V pp to 20.0V pp (1 kΩ into 50 Ω).

ACCURACY:	Sine	Square	Triangle (50%)	Ramp (20%,80%)	Pulse (20%,80%)
<1 kHz	±2%	±2%	±2%	±2%	±2%
1 kHz - 5 MHz	±2%	±2%	±2%	±5%	±2%
5 MHz - 20 MHz	±5%	±5%	±10%	±10%	±5%
20 MHz - 50 MHz	±5%	±5%	+5, −20%	-	-

RESOLUTION: 3 digits.

OFFSET: 0 to ±5.00V,
0 to ±10.0V (1 kΩ into 50Ω).

ACCURACY: ±(1% programmed value + 1% signal V pp + 20 mV).

RESOLUTION: 2 digits (10 to 99 mV), 3 digits (≥100 mV).

SINE CHARACTERISTICS (Norm Mode):

HARMONIC COMPONENTS: Up to 5 MHz, THD<1% of fundamental. Above 5 MHz, all harmonics at least 30 dB below fundamental.

SPURIOUS: All non-harmonically related outputs at least 40 dB below fundamental.

TRIANGLE/RAMP CHARACTERISTICS

SYMMETRY: 20, 50, 80% selectable.

LINEARITY (10% to 90%): ±1% (up to 5 MHz).
±5% (above 5 MHz).

SQUARE/PULSE CHARACTERISTICS:

DUTY CYCLE: 20, 50, 80% selectable.

TRANSITION TIMES (10% to 90%): <5 ns,
<7 ns (1 kΩ into 50Ω).

PRESHOOT/OVERSHOOT/RINGING: ±5%,
±10% (1 kΩ into 50Ω).

Operating Modes

NORM: continuous waveform is generated, phase-locked to an internal 10-MHz crystal reference.

VCO: external voltage (100 kHz max) from 10 mV to 10V linearly sweeps 3 decades up to top of decade in which the 8165A frequency is set. Four bands limited to less than 3 decades:

100 mV - 10V for 100 kHz - 10 MHz
and 10 Hz - 1 kHz,
10 mV - 2V for 100 kHz - 20 MHz,
50 mV - 5V for 500 kHz - 50 MHz.

TRIG: pos ext input pulse ≥10 ns wide generates one output cycle. Upper level ≥+250 mV, lower level ≤0V.

GATE: oscillator enabled when ext input ≥+250 mV, disabled when ≤0 V. First and last output cycles are always complete.

BURST: a preprogrammed number of output cycles is generated. Min. time between bursts 50 ns. Burst length 0 to 9999 cycles. Min. trigger pulse width 10 ns, upper level ≥+250 mV, lower level ≤0V.

FM: 0 to ±1V modulates 0 to ±1% deviation.

MODULATING FREQUENCY: 100 Hz to 20 kHz (Norm mode), dc to 20 kHz (Gate mode with carrier frequency ≥1 kHz).

INPUT IMPEDANCE: 10 kΩ typical.

AM (Option 002 only): 0 to 2.5V pp modulates 0 to 100% modulation depth.

MODULATING FREQUENCY: dc to 10 MHz (−3 dB).

INPUT IMPEDANCE: 10 kΩ typical.

PULSE MODULATION: transition times <50 ns.

ENVELOPE DISTORTION (dc to 250 kHz mod freq):

Carrier	Modulation	Distortion
≤1 MHz	0 to 90%	<1%
>1 MHz	0 to 30%	<3%

CARRIER FREQUENCY DEVIATION: <0.01%, 0 to 30% modulation.

SWEEP: (Option 002 only): provides logarithmic up/down sweep up to 3 decades between limits set on the 8165A. As in VCO mode, 4 bands limited to less than 3 decades. Min frequency 1 mHz.

SWEEP-RATE: 0.01, 0.1, 1, 10, 100, 1000 seconds per decade selectable.

TRIGGER: one up-down sweep per trigger pulse (upper level ≥+250 mV, lower level ≤0V, width ≥10 ns).

ACCURACY: sweep start frequency ± (15% + 0.5% of max. stop frequency), sweep stop frequency ±15%.

RESOLUTION: 2 digits.

Auxiliary Outputs and Inputs

EXT. INPUT: external signals used in VCO, Trig, Gate, Burst and (Option 002) Sweep ext. trig.

SIGNAL RANGE IN VCO: 10 mV to 10V for 3-decade sweep.

SIGNAL THRESHOLDS IN TRIG, GATE, BURST, SWEEP EXT. TRIG: + 250 mV (upper), 0V (lower).

MAX. INPUT: ±20V,

INPUT IMPEDANCE: 10 kΩ typical.

SYNC. OUTPUT: one trigger pulse per main output cycle.

AMPLITUDE: 3 V pp into open circuit (1.5V pp into 50Ω).

EXT. 10-MHz REF: external 10 MHz, TTL, system clock. Rear-panel switch selects ext or int clock as instrument reference.

MOD INP: FM and (Option 002 only) AM input.

SIGNAL RANGE IN FM: 0 to ±1V for 0 to ±1% deviation.

SIGNAL RANGE IN AM: 0 to 2.5V pp for 0 to 100% modulation depth.

MAX. INPUT: ±20V.

INPUT IMPEDANCE: 10 kΩ typical.

SWEEP OUT (Option 002 only): triangular sweep voltage, 0 to 2.99V amplitude for 3 decades (1V/decade).

HP-IB Capability and Microprocessor

CODE	INTERFACE FUNCTION
SH 1	Source Handshake Capability
AH 1	Acceptor Handshake Capability
T 6	Talker (basic talker, serial poll, unaddress to talk if addressed to listen)
L 4	Listener (basic listener, unaddress to listen if addressed to talk)
SR 1	Service Request Capability
RL 1	Remote/Local Capability
PP 0	No Parallel Poll Capability
DC 0	No Device Clear Capability
DT 1	Device Trigger Capability
C 0	No Controller Capability
E 1	Three-state Bus Drivers

ACCURACY: See Frequency and Output Characteristics.

SETTLING TIMES:

FREQUENCY: <20 ms to ±5% of programmed value. In Norm mode, and in Trig, Gate, Burst at frequencies <1 kHz:
<70 ms to ±2% of programmed value,
<300 ms to final value.

OTHER FUNCTIONS: 20 ms. The following range changes can take up to 200 ms:
Change of duty cycle.
Selection to or from Sweep/VCO.
Changing up to/down from the following decades:
Frequency 1 kHz, 10 kHz, 100 kHz, 1 MHz, 20 MHz.
Amplitude 100 mV, 1V
Offset 1V.

NUMBER OF BYTES SENT/RECEIVED

LISTENER: up to 65 bytes (89 in Option 002) for one complete set of operating parameters.

TALKER-LEARN MODE: 8 lines. Each line up to 16 bytes plus CR LF. Total: 144 bytes max.

TALKER-ERROR MESSAGE: 1 byte.

BYTE RATE:

FUNCTION TIME (typical values): set up as talker/listener 1.1 ms, receiving time per character 0.1 ms, processing per parameter 3.0 ms, entry time per digit 2.0 ms, check time per parameter entry 5-10 ms, waveform/duty cycle/modulation 1.0 ms, input mode 6.5 ms, output modes 9.0 ms, recall 25 ms, store 380 ms.

MEMORY: 10 addressable locations plus one for existing operating state.

CAPACITY: each location can store a complete set of operating parameters and modes.

ACCESS TIME: 20 ms each location.

STORAGE TIME: internal battery provides memory retention for approx. 4 weeks at room temperature. Battery recharges when 8165A is switched on.

General

POWER REQUIREMENTS: 100V, 120V, 220V, or 240V; +5 to −10%, 48 to 66 Hz, 200 VA max.

ENVIRONMENTAL: operates to specifications from 0 to 50°C, and with relative humidity to 95% at 40°C.

STORAGE: −20 to +70°C.

WEIGHT: net 12 kg (26.5 lb). Shipping 16 kg (35.3 lb).

DIMENSIONS: 426 mm W × 145 mm H × 450 D (16.8 × 5.7 × 17.7 in).

PRICE IN U.S.A.: $6145; Opt. 002, $710.

MANUFACTURING DIVISION: HEWLETT-PACKARD GmbH
Herrenberger Strasse 110
D-7030 Boeblingen-Wuerttemberg
Germany

A Compact Logging Multimeter that Can Manipulate Data

By combining the attributes of a 4½-digit multimeter, a thermometer, a 4-channel scanner, a printer, and a microprocessor, this versatile instrument can be a time-saver for the design engineer.

by John E. Scruggs, Marsh L. Faber, and David L. Wolpert

TIME IS VALUABLE—just as much so in the design lab as anywhere else. That provided the motivation for a project that culminated in the Model 3467A Logging Multimeter (Fig. 1). The goal was: develop an instrument that saves design time.

Capable of handling a major part of the measurements required during the course of a typical electronic design effort, this self-sufficient instrument measures ac and dc voltages, resistance, and, with external thermistors, temperature. It has a four-channel scanner, a thermal printer for permanent records, and an internal timer that allows unattended measurements. The instrument requires no external control or I/O, yet it can perform computations on measurement data under pushbutton control.

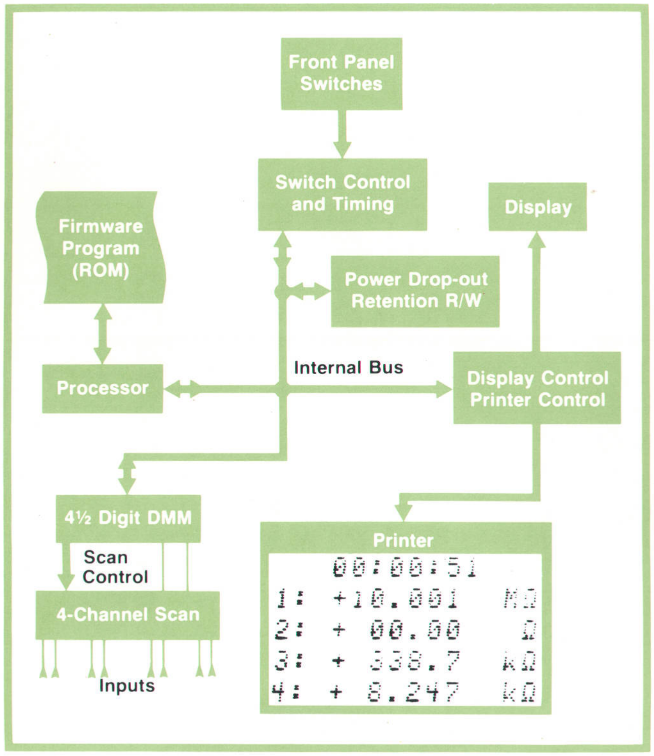
The nucleus of this instrument is a 4½-digit, autoranging multimeter, basically similar to the HP Model 3466A Digital Multimeter. The printer is a compact, moving-head, dot-matrix, thermal printer similar to those used on the HP-91 and HP-97 Calculators.[1] Scanning is by means of reed relays. A microprocessor provides the communication between the multimeter, scanner, timer, and printer, as shown in the block diagram of Fig. 2.

Data Manipulation

Inclusion of a microprocessor allowed math operations to be implemented. Among other things, these make it possible to linearize and convert readings of thermistor resistance measurements to readings of temperature in °F or °C.

Other operations performed with the math functions involve the use of channel 4 as a reference, designated "Y." Any of the other three channels, de-

Fig. 1. *The Model 3467A Logging Multimeter is basically a 4½-digit multimeter with a built-in four-channel scanner and a printer, all controlled by an internal microprocessor. The microprocessor can also translate raw measurement data into more useful forms, such as linearizing and converting thermistor measurements to give readings directly in °F or °C.*



```
   00:00:51
1: +10.001   MΩ
2: + 00.00    Ω
3: + 338.7   kΩ
4: + 8.247   kΩ
```

Fig. 2. *Organization of the Model 3467A Logging Multimeter.*

signated "X," may then operate on the reference so measurement results can be presented in the most useful form. The possible operations are:

Δ	$(X-Y)$	÷	(X/Y)
Δ%	$(\frac{X-Y}{Y}) \times 100$	dB	$20\log\lvert X/Y\rvert$
*	XY		

Besides using measurements made on the Y channel as the Y reference, arbitrary values of Y can be entered and stored for use as constants for the math functions. The MATH pushbuttons normally are interlocking so only one at a time can be depressed, but the switch assembly has been modified such that when the Y pushbutton is depressed, the MATH buttons function as momentary contact switches. Each of these can then be used to step one of the display digits to any desired value. The dB pushbutton steps the decimal point to the desired position. Releasing the Y pushbutton stores the displayed number for subsequent use as the Y reference.

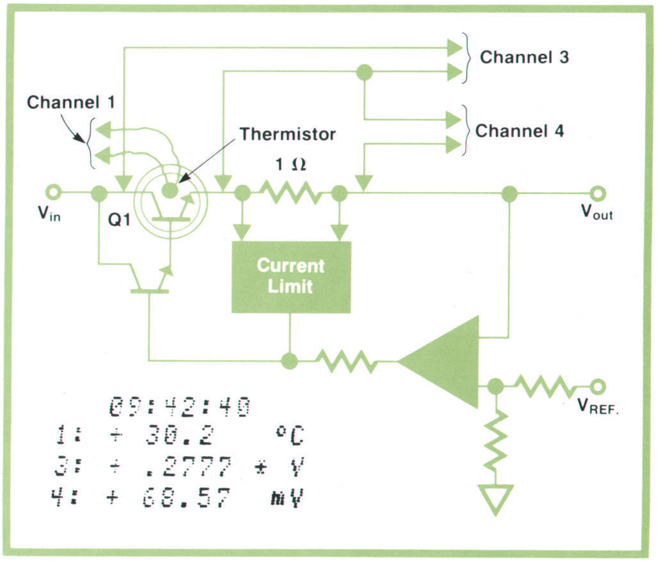
Additional uses of the math capability involve offsets. With the input leads shorted, usually at the point of measurement, pressing the μV,Ω ZERO pushbutton stores any residual voltage or resistance reading as an offset for that channel. This offset, which can be as high as 2 mV or 20Ω, is then automatically subtracted from subsequent measurements.

Applications

Of what use are these capabilities to the engineer on the bench? Characterizing amplifiers and filters directly in dB units is one example. With channel 4 measuring the input to the device, any of the other channels measuring the output, and the dB button pressed, readings will be given directly in dB units.

With the appropriate value entered as the Y constant, measurements on channels 1, 2, and 3 can be made in dBm referred to any impedance desired. For example, the voltage V for 1-mW dissipation in a characteristic impedance R_c is derived from the relationship: $V^2/R_c = P$, where $P = 1\text{mW}$. For a 600Ω impedance, V is 0.7746 volts. With this value entered as the Y reference and the dB button pressed, the results of voltage measurements will then be displayed in dBm referenced to 600Ω. Obviously, this kind of capability makes the instrument as useful on the production line as on the designer's bench.

When the TEMP function button is pressed at the same time as one of the other functions (⎓V, ~V, or kΩ), temperature can be measured on channels 1 and 2 while channels 3 and 4 measure the other function. An example of how this "mixed" mode can be used is shown in Fig. 3. Here, the effectiveness of the heat sink used on a power supply regulator is being evaluated. A thermistor is cemented to the case of the regulator transistor and the temperature there is measured on channel 1. Channel 3 monitors the voltage drop across the transistor while channel 4 measures the current (A × 1Ω = V). With the * MATH button



```
   09:42:40
1: + 30.2    °C
3: + .2777 * V
4: + 68.57   mV
```

Fig. 3. *The thermal performance of a heat sink for a series-regulator transistor is evaluated with the help of the logging multimeter in the setup shown here. The printout shows temperature at the surface of the transistor (channel 1), the power dissipated by the transistor (channel 3), and the load current (channel 4). The instrument multiplies the voltage measured on channel 3 by the channel 4 current reading (mV = mA ×1Ω), which functions as the Y reference, to give the transistor power dissipation (0.2777 W).*

depressed, the logging multimeter multiplies the channel 3 reading by the channel 4 reading to give the power dissipated in the transistor. The power supply load can then be varied and a printout obtained by manual pushbutton each time the temperature stabilizes at a new value. Note that the load current (channel 4) is also printed. A second thermistor could be connected to channel 2 to give a simultaneous record of ambient temperature.

With the internal timer, up to four measurement points can be scanned and the results printed at specified time intervals. These intervals range from less than ten seconds up to three hours. This enables unattended monitoring of such quantities as voltage drift versus time during device warmup, and battery charge/discharge characteristics.

Power Drop-Out Protection

With offsets and/or a Y constant stored, it would be at least disconcerting and possibly even disastrous if a power-line transient or momentary power loss caused these constants to be lost, especially if the instrument were operating unattended. To guard against this, the Model 3467A has a power dropout protection circuit that saves entered constants for at least five seconds in the event of a power loss. The circuit is shown in Fig. 4.

While the system is running, data such as the Y reference, offsets, elapsed time, and the next print time are read from the microprocessor memory and stored in a low-power CMOS read-write memory (RAM) each time the display is updated. If line power fails sufficiently long for V_{cc} to fall below 4.83V, the processor system will be disabled, but the data in the low-power RAM will be retained by the voltage on a capacitor (voltage V_c on capacitor C_A). When power returns, the processor, upon resuming operation, first checks the output of the stored-voltage comparator. If this indicates that the voltage V_c on capacitor C_A is still greater than 2V, it loads the data stored in the low-power RAM into the corresponding locations in its own memory. Instrument operation then continues as before. The printer, however, inserts an extra line feed before the next printout to indicate that a power drop-out occurred.

If V_c is less than 2V when power is restored, the processor initializes the stored Y constant to +1, and the other constants, offsets, and times are set to zero.

The circuit shown in Fig. 4 includes two safeguards. Switch Q1, a transistor, is controlled by the power-on reset signal, a delayed version of the power-valid signal. This allows capacitor C_A to charge only while the processor is operational and data in the CMOS memory is valid. The front-panel line power switch has an additional pole that provides a discharge path for capacitor C_A when the power is switched off. Whenever this switch is toggled, the stored values are reinitialized as above.

Scanning High Voltages

One problem that was resolved during the design of this instrument was the deleterious effect that high voltages can have on scanner relays when floating measurements are made. Fig. 5 illustrates this.

If one side of a voltage source (±350V dc max.) is connected to safety ground and the other is connected to a channel's input Lo (Fig. 5a), a large charging current is switched by the scanner relay S1. This is because the distributed capacitance on the LOW side is relatively large (500-1000 pF), a result of the large area of sheet metal connected to circuit LOW. If switched repeatedly, which would be the case when scanning, this current would eventually pit the relay contacts and cause erratic operation.

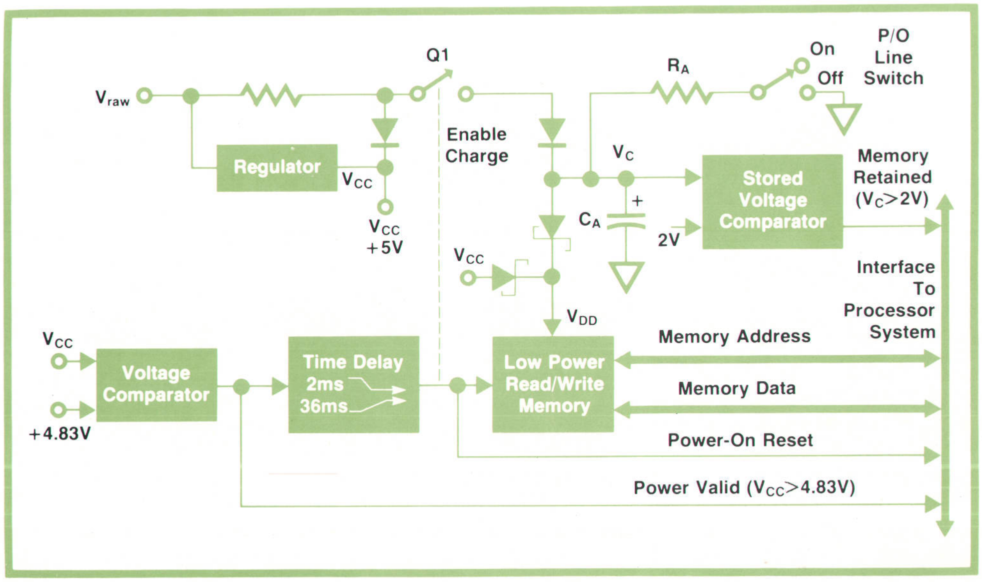


Fig. 4. *Power dropout protection circuit retains math constants and other data in a CMOS memory powered by the charge on capacitor C_A. Data is retained for at least five seconds if line power fails.*

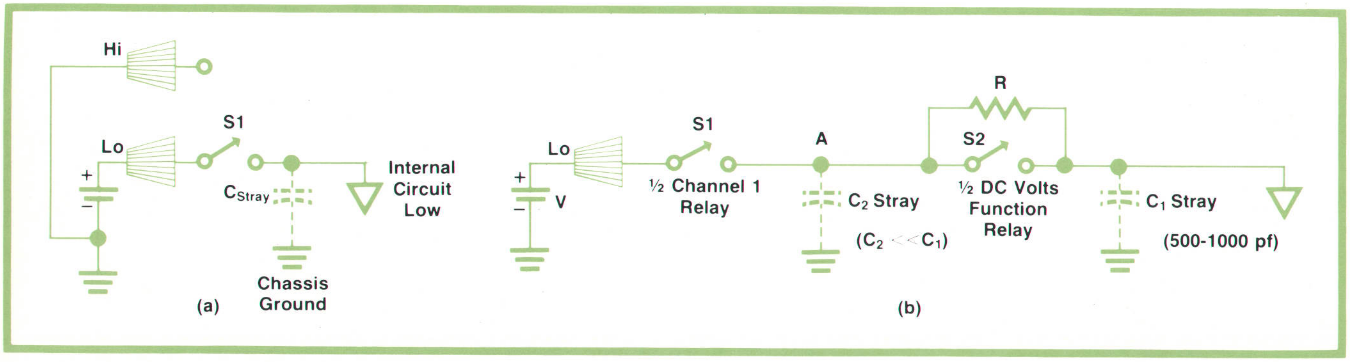


Fig. 5. *Relay closings are sequenced (S1 before S2) so neither relay has to switch the full current that charges stray capacitance C1. This avoids the damage to the relay points that repetitive switching of high currents can cause.*

The solution was to sequence the relays so the scanner relay (S1) closes before the function relay (S2 in Fig. 5b). Point A in Fig. 5b is not connected directly to the floating chassis sheet metal so the distributed capacitance at that point is very small. When S1 is closed, this small capacitance (C2) charges very quickly while C1 charges relatively slowly through resistor R. S2 is timed to close after C2 is fully charged. Thus, neither switch is required to switch any appreciable current, resulting in much better reliability in high-voltage measurements.

In the event that a scanner relay should fail in a closed position, it is possible that two measured sources would be connected together when the next channel relay closes. To prevent damage to the sources, a fuse is placed in series with each channel's input. This adds series resistance, but this resistance is effectively "nulled out" of resistance measurements by the zeroing and offset storage procedure.

David L. Wolpert

Dave Wolpert joined HP Loveland Instrument Division in 1972, immediately after receiving his BEE degree from the Georgia Institute of Technology. He was initially involved in several lab investigation projects and subsequently became a designer for the 3495A Scanner. Responsible for the digital hardware and software for the 3467A Logging Multimeter, Dave now works in LID production engineering. A resident of Loveland, Colorado, Dave has also taught electronics technology classes at a local community college. Dave's interest in electronics extends beyond the regular workday. He is currently writing a cassette tape operating system and a business-oriented software supervisor for his home computer system. Dave also enjoys photography, drama, playing guitar and piano, and working at a local recording studio.

John E. Scruggs

Born and raised in Dallas, Texas, John Scruggs is a 1964 New Mexico State University graduate with a BSEE degree. He worked for five years on Apollo and Mariner spacecraft electronics while taking night classes at Arizona State University, where he eventually received his MSEE degree. After another three years as a control systems designer for a monorail vehicles company, he joined HP in 1973. John was initially project manager on a computer-based LSI test system in the Loveland integrated-circuit department. He then transferred to the research and development lab where he worked in several investigations before becoming project manager for the 3467A Logging Multimeter. John, his wife and three daughters, ages seven, ten and thirteen, raise and show quarter horses. John also enjoys playing the guitar and participating in competitive sports such as basketball and tennis.

Marshall L. Faber, Jr.

Marsh Faber joined HP in 1966, shortly after receiving his BSEE degree from the University of Denver. He began work as production engineer on DVMs while studying toward his master's degree at Colorado State University in the HP Honors Coop Program, receiving his MSEE degree in 1971. More recently, Marsh contributed to the design of the 3435A DVM and the 970A Probe Digital Multimeter. At the 1974 IEEE electronic components conference, he received best paper award for his paper entitled "Algorithmic Trimming on Active Circuitry." Born in Washington, D.C., Marsh is married with two children, ages three and five. He enjoys fishing, home improvement, skiing, tennis, racquetball and charcoal sketching. Marsh is also a guitarist and enjoys composing songs as well as playing.

SPECIFICATIONS
HP Model 3467A Logging Multimeter

DC Voltmeter

Range	Maximum Reading
20mV	19.999mV
200mV	199.99mV
2V	1.9999V
20V	19.999V
200V	199.99V
350V	349.9V

MAXIMUM INPUT: ±350 V from any terminal to ground and between any two terminals.
RANGING: Automatic or Hold/Step.
SENSITIVITY: 1 µV on 20mV range.
POLARITY: Automatically sensed and displayed.
ZERO ADJUSTMENT: Front-panel pushbutton compensates for up to ±2 mV offset for each channel.
ACCURACY (6 months, 18°C to 28°C):

Range	±(% of reading + number of counts)
20 mV	0.05 + 10
200 mV	0.04 + 2
2V–200V, 350V	0.03 + 1

TEMPERATURE COEFFICIENT: (0° to 18°C, 28° to 50°C): ±(0.003% of reading + 0.15 counts)/°C.
INPUT RESISTANCE: 10 MΩ ± 5% on all ranges.
NORMAL MODE REJECTION: >60 dB at 50/60 Hz ± 0.1%.
EFFECTIVE COMMON MODE REJECTION (1 kΩ unbalance): >120 dB at 50/60 Hz ± 0.1%.
SINGLE CHANNEL RESPONSE TIME (without printing): <0.7 seconds to within 1 count of final value on one range. Add 0.8 seconds for each range change.

Ohmmeter

Range	Maximum Reading	Current Through Unknown
200Ω	199.99Ω	5mA
2kΩ	1.9999kΩ	1mA
20kΩ	19.999kΩ	100µA
200kΩ	199.99kΩ	10µA
2MΩ	1.9999MΩ	1µA
20MΩ	19.999MΩ	100nA

INPUT PROTECTION: 250 V rms or 350 V (dc + peak ac).
RANGING: Automatic or hold/step.
SENSITIVITY: 10 mΩ on 200Ω range.
CONFIGURATION: 2-wire with front-panel pushbutton zero adjustment. Lead resistance of up to 20 Ω can be nulled out for each channel.
ACCURACY (6 months, 18°C to 28°C):

Range	±(% of reading + number of counts)
200Ω	0.08 + 10
2kΩ	0.03 + 3
20kΩ – 200kΩ	0.03 + 1
2MΩ	0.04 + 1
20MΩ	0.15 + 1

TEMPERATURE COEFFICIENT:

Range	(0°C to 18°C, 28°C to 50°C)
200Ω	±(0.002% of reading + 1 count)/°C
2kΩ–2MΩ	±(0.002% of reading + 0.1 count)/°C
20MΩ	±(0.01% of reading + 0.1 count)/°C

OPEN CIRCUIT VOLTAGE: <5 V.
SINGLE CHANNEL RESPONSE TIME (without printing): <1.1 seconds to within 1 count of final value on one range. Add 0.8 seconds for each range change.

Diode Test

FUNCTION: kΩ ▶|
RANGE: 2kΩ
CURRENT SOURCE: 1mA ± 4%
DIODE VOLTAGE DROP DISPLAYED IN VOLTS: 1.9999 volts maximum measurable voltage.

AC Voltmeter

AC CONVERTER: True rms responding and calibrated in true rms; ac coupled.

Range	Maximum Reading
200mV	199.99mV
2V	1.9999V
20V	19.999V
200V	199.99V
250V	249.9V

MAXIMUM INPUT: ±350 V (dc + peak ac), 10^7 V·Hz from any terminal to ground and between any two terminals.
RANGING: Automatic or Hold/Step.
CREST FACTOR: 4:1 at full scale.
ACCURACY:
Accuracy applies with readings of ≥9% full scale (≥1800 counts on 250V range); 6 months, 18°C; sinusoidal waveform.

Frequency	±(% of reading + number of counts)
45Hz–100 Hz	1 + 40
100 Hz–10 kHz	0.2 + 40
10 kHz–20 kHz	1 + 40
20 kHz–100 kHz	2 + 200

TEMPERATURE COEFFICIENT:

Frequency	(0°C to 18°C, 28°C to 50°C)
45 Hz–100 Hz	± (0.05% of reading + 2 counts)/°C
100 Hz–10 kHz	± (0.03% of reading + 2 counts)/°C
10 kHz–20 kHz	± (0.05% of reading + 2 counts)/°C
20 kHz–100 kHz	± (0.05% of reading + 15 counts)/°C

INPUT IMPEDANCE: 2 MΩ ±5% in parallel with <100 pF.
SINGLE CHANNEL RESPONSE TIME (without printing): <2 seconds to within 4 counts of final value on one range. Add 1.2 seconds for each ranch change.

Temperature Measurement

TECHNIQUE: Temperature measurements using thermistors can be made directly in °C or °F, selectable by an internal switch. Thermistor linearization is included for the following thermistors: Yellow Spring 44007, Omega UUA 35J3, Fenwal UUA 35J1 or equivalent. (One thermistor is furnished with each 3467A).
ACCURACY (includes ohmmeter accuracy, thermistor curve fit accuracy, and thermistor self-heating):
−80°C to +80°C: ± 0.3°C;
+80°C to +110°C: ± 0.5°C;
+110°C to +150°C: ± 1.3°C.

Four-Channel Scanner

TYPE: One 2-pole, low-thermal, dry-reed relay per channel.
INPUTS: Floating inputs. Any combination of four channels may be selected to measure one of the following functions: dc volts, true-rms-ac volts, resistance, or temperature. Measurements of temperature on channels 1 and 2 and either dc volts, ac volts, or resistance on channels 3 and 4 can also be made.
CHANNEL-to-CHANNEL ISOLATION:

Source Impedance	Up to 1 kHz	Up to 100 kHz
600Ω	>100 dB	>60 dB
10kΩ	> 80 dB	>40 dB

Printer and Timer/Pacer

TYPE: Thermal Printer.
PRINT MODES:
MANUAL: Initiates a printout of selected input channels.
AUTOMATIC: Scans, measures and prints selected input channels at preset time intervals.
TIME INTERVAL:* 1, 3, 6, 10, 18, 30, 60, or 180 seconds or minutes interval selectable via front-panel pushbuttons.
TIMER: Internal 24-hour crystal controlled interval timer. Timer starts at 00:00:00 (HH:MM:SS). Time offset can be manually entered to synchronize timer with the time of day.
TIMER ACCURACY: Within 1 minute in 24 hours.
POWER FAILURE PROTECTION: Should a power failure occur, the 3467A will retain the math constant, elapsed time, offsets, and ranges for up to 5 seconds.

*Time intervals ≤10 seconds may be shorter than actual time required to completely measure and print selected channels. In these cases, next printout will be initiated upon completion of present scan sequence.

General

READING RATE: Depends on input signal level. 2 to 4½ readings/second.
OPERATING TEMPERATURE: 0°C to +50°C.
HUMIDITY: 95% R.H., +15°C to 140°C without thermal paper. 60% R.H., +15°C to +30°C with thermal paper.
POWER: 100/120/220/240 + 5%, −10%, 48 to 440 Hz, <25 VA.
DIMENSION: 190.5 mm H × 212.9 mm W × 304.8 mm D (7½ × 8⅜ × 12 in.).
WEIGHT: 4.77 kg (10.5 lb).
PRICE IN U.S.A.: 3467A (including 1 roll of thermal paper and 1 thermistor): $2200.
MANUFACTURING DIVISION: LOVELAND INSTRUMENT DIVISION
P.O. Box 301, 815 Fourteenth Street, S.W.
Loveland, Colorado 80537 U.S.A.

Acknowledgments

Ed Pennington and Mike Williams were responsible for the product design and Ralph Swanson handled the industrial design. Ron Firooz contributed to the software. A special thanks to Dave Palermo and Roy Barker who fathered the idea for the project. Thanks also to Bob Hetzel, Lois Bryan and Dave Connell for their support during release to production.

Reference

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Road, Palo Alto, California 94304

HEWLETT-PACKARD JOURNAL
DECEMBER 1978 Volume 29 • Number 16

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