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A Self-Contained, Hand-Held Digital Multimeter—A New Concept in Instrument Utility

Aside from clipping the coiled lead to any convenient reference point, only one hand is needed to hold this instrument, and take a reading.

by Robert L. Dudley and Virgil L. Laing

IT IS GENERALLY ACCEPTED that a multimeter for measuring voltage and resistance is an indispensible tool for service specialists, technicians and engineers. There have been many improvements in the last few years, such as digital readout, high input impedance, better accuracy and resolution, and these improvements have helped the user make measurements more precisely with fewer errors. Little has been done, however, to make the multimeter easier to use and better suited to the technician or engineer who needs to make fast measurements in hard-to-get-at places.

Shown in Fig. 1 is a new battery-powered 3½ digit Probe Multimeter that is completely self-contained and can be held and operated in one hand. The instrument has autoranging, autopolarity, and autozero, which means the user need only set the function switch and depress the power bar to get an accurate reading.

To use the instrument, the coiled lead is attached to a suitable ground or reference point, and the probe tip is placed on the point to be measured. When the power switch is pressed, the voltage or resistance value appears on the display with range and polarity automatically selected.

Several advantages of this probe configuration are apparent. Portability is an obvious one, and the location of the display close to the point of measurement speeds reading time while eliminating the need to shift the eyes to get a reading.

Another advantage is the ability to invert the display to facilitate readings when the Probe is held upside-down to reach a hard-to-get-to place (Fig. 2). In addition, the probe tip can be pivoted into three detented positions: straight, tilted at 30°, and tilted at 60°. The tip can be folded back so that the Probe can be carried in a pocket or the belt-carrying case provided with the instrument.

A Real Instrument

This hand-held instrument is a true digital multimeter with three digits of readout plus a "1" for 10% overranging. The most sensitive range for both ac and dc measurements is 100 mV full scale with 0.1 mV resolution. Although the input is protected up to 1000 V, for safety reasons the maximum input voltage is specified at 500 V.

The accuracy of readings is better than 1% for dc voltages and between 2 and 5% for ac. The input

Cover: *The hand-held digital multimeter-a concept that's been in the back of many an engineer's mind ever since integrated circuits went large-scale-has become a reality. Doing it required more than an integrated circuit, however; it required a combination of technologies as described here. (Zero is added to 3-digit display here to indicate range.)*

In this Issue:

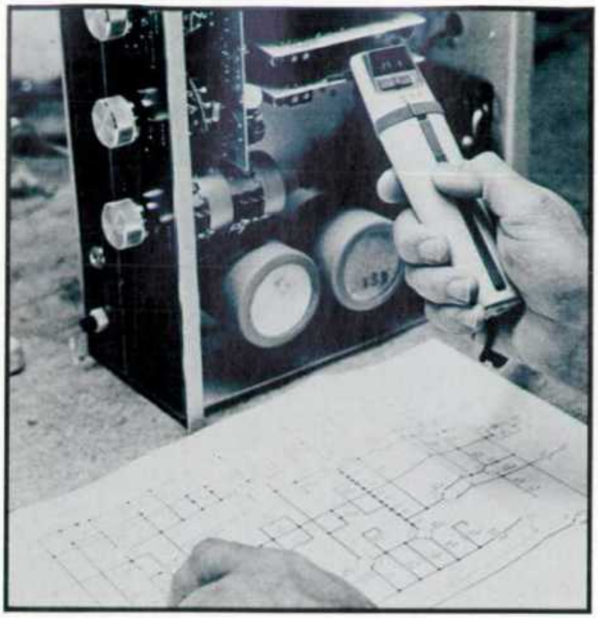

Fig. 1. *Model 970A Digital Multimeter was designed for convenient hand-held operation. The user needs only to select the desired function and press the power switch (the long, flat bar) to take a reading; the instrument automatically selects the right measurement range.*

impedance is 10 megohms paralleled by less than 30 pF. The ac frequency range is up to 3500 Hz, wide enough for power line and most voice-channel measurements.

As an ohmmeter, the new multimeter has full-scale ranges from 1 to 10,000 kilohms with a resolution of 1 ohm on the lowest range. The accuracy of ohms readings is better than 2%. In all functions, the instrument displays a reading in less than 2 seconds after the switch is pressed (to speed this up, it starts at mid-range and then ranges in the appropriate direction). In continuous operation, it makes 3 readings per second.

The Ni-Cad batteries that power the instrument can operate continuously for a minimum of 2½ hours before needing recharge, but by pressing the switch only when a reading needs to be taken, the user can make at least 2000 readings on one charge. The power switch has a lock position for those occasions when continuous monitoring may be desired. For recharge, the batteries slip out of the instrument and into a charger that plugs into a wall outlet (see Fig. 12). Where heavy use is anticipated, an extra set can be obtained so one set can be recharging while the other is used in the instrument.

Design Philosophy

The original objective at the start of the design phase was to design a 3½-digit multimeter at the lowest possible cost consistent with traditional HP dependability. As the circuit design evolved it became apparent that the circuits could be contained within a surprisingly small space at modest cost, using recently-developed monolithic and thin-film hybrid integrated-circuit technologies. Thus, a hand-held, self-contained instrument was a possible configuration to be considered.

Other than the obvious operating conveniences, other advantages would accrue from a hand-held configuration. Since the display would be close to the point of measurement, it would not have to be read from a distance and therefore could be small and more economical. The miniature LED display developed for the HP hand-held calculators was ideal for this situation, and it uses less power than a larger display. Since the display could be in line and close to the point of measurement, a press-to-read type of operation could be used to further conserve power. Hence smaller batteries could be used. It was decided, then, to place project emphasis on providing the multimeter capability in a hand-held instrument.

Many shapes and configurations were evaluated. The elliptical cross-section was adopted as this fits the hand comfortably while providing a tactile clue as to the orientation of the instrument. In keeping with the concept of hand-held convenience, the case surface is textured to minimize slippage. The problem of where to place a multi-position function switch was solved by development of the "watchband" switch. The power switch was designed as a bar that can be operated along most of its length. This, plus the invertible display and swiveled

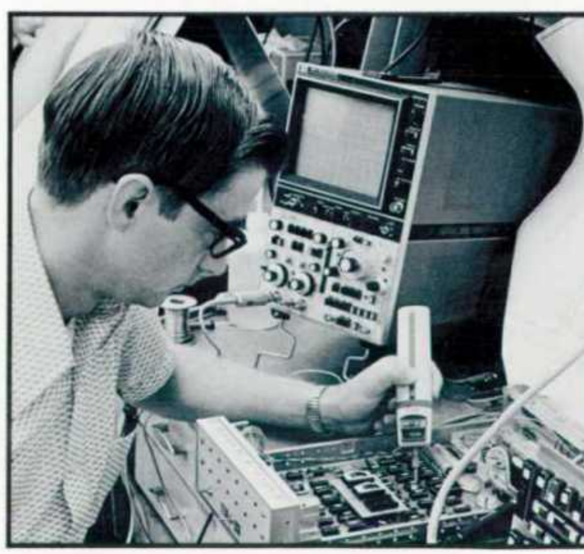

Fig. 2. *Slide switch adjacent to the display inverts the numerals so readings can be taken with the probe upside down.*

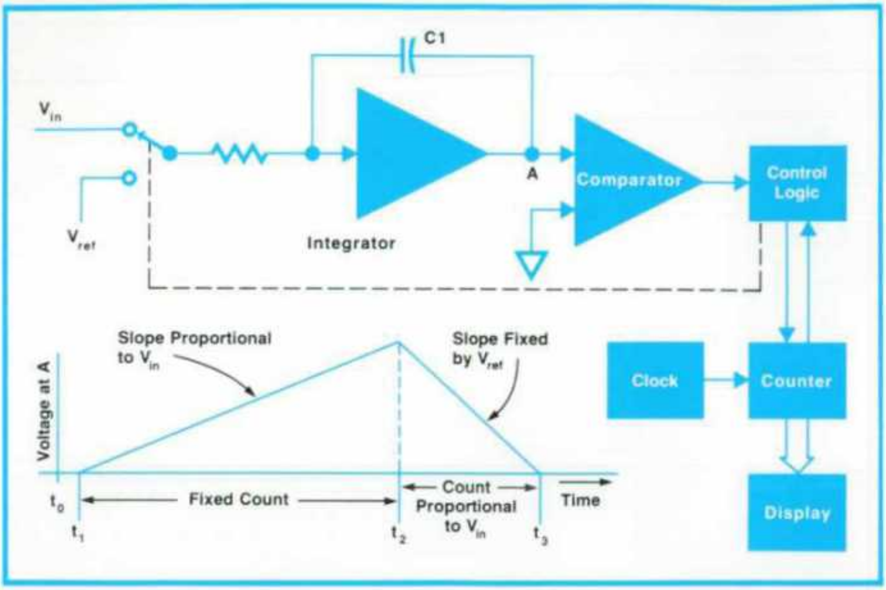

Fig. 3. *Digital-to-analog conversion by the dual-slope technique is essentially a voltage-to-time conversion with digital measurement of the resulting time interval.*

probe tip, allows the instrument to be used conveniently in a variety of positions. To protect the user against accidental contact to high voltages, the instrument was designed so there are no exposed metallic parts anywhere on the instrument, except for the probe tip and the ground clip.

Inside

The Probe Multimeter is an integrating digital voltmeter that employs the widely-used dual-slope technique to derive a digital display from a dc voltage. Although described recently in this publication[1], the description is repeated here for the sake of completeness.

With reference to the timing diagram of Fig. 3, at time t_1 the unknown input voltage V_{in} is applied to the integrator. Capacitor C1 then charges at a rate proportional to V_{in}.

The counter starts totalizing clock pulses at time t_1 and when a predetermined number of clock pulses has been counted, the control logic switches the integrator input to V_{ref}, a known voltage with a polarity opposite to that of V_{in}. This is at time t_2. Capacitor C1 now discharges at a rate determined by V_{ref}.

The counter is reset at time t_2 and again it counts clock pulses, continuing to do so until the comparator indicates that the integrator output has returned to the starting level, stopping the count. This is at time t_3.

The count retained in the counter is proportional to the input voltage. This is because the time taken for capacitor C1 to discharge is proportional to the charge acquired, which in turn is proportional to the input voltage. The number in the counter is then displayed to give the measurement reading.

The attractive characteristic of this technique is that many of the variables are self-cancelling. For example, long-term changes in the clock rate or in the characteristics of the integrator amplifier, resistor, or capacitor affect both the charge and discharge cycles alike. Considerable long-term deviation from normal values can be tolerated without introducing errors.

Also, since the input voltage is integrated during the up slope, the final charge on C1 is proportional to the average value of the input during the charge cycle. Noise and other disturbances are thus averaged out and have a reduced effect on the measurement. In particular, by making the charging cycle equal to an integral number of power line cycles, the effect of any power line hum is reduced by a substantial amount.

The Overview

A block diagram of the new multimeter is shown in Fig. 4. The input is applied to amplifier A1, which has feedback resistors that can be switched to change gain and hence the sensitivity range. The 10-megohm resistor in series with the input, besides being an essential part of the amplifier configuration, also provides protection against high input voltages.

The offsets in the amplifiers and integrator are compensated for by an autozero technique similar to that used in other HP digital multimeters.[1] Just prior to the integration cycle (see Fig. 4), MOSFET switches disconnect the input signal and connect a matching 10-megohm resistor to the input of amplifier A1. In the autozero mode, the comparator operates as a high-gain amplifier and a feedback loop is

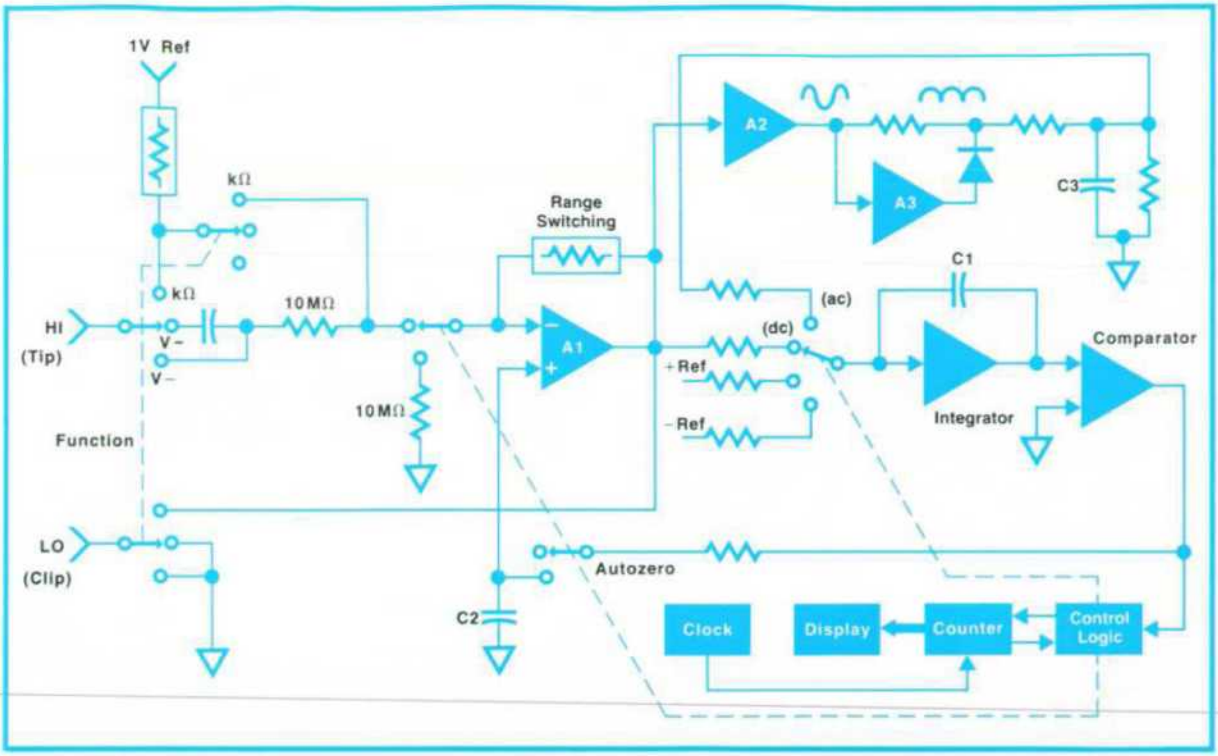

Fig. 4. *Simplified block diagram of Model 970A Digital Multimeter. Except for the FUNCTION switch, all the switches shown here are MOSFET switches on the main monolithic IC chip.*

closed around the input amplifier, integrator, and comparator, charging the autozero capacitor C2 to a voltage that compensates for the offset voltages in the entire feedback loop. When the input is reconnected to amplifier A1, the feedback to C2 is disconnected but the charge on C2 remains during the measurement to compensate for the offsets. The autozero circuit thus eliminates the requirement for a zero-adjust potentiometer.

Following the input amplifier, dc voltages are applied to the integrator for conversion to digital form. A number of changes were made, however, to the standard dual-slope integration to enhance the operation of the Probe Multimeter. For example, by using an integration time of 1/6 second on some ranges rather than 1/60 second (1/5 and 1/50 second in European versions), sensitivity can be increased by a factor of 10. Then, only three range resistors, providing 100:1 steps, are needed in the input amplifier with switching of the integration time to give the 10:1 range steps. This reduces the number of resistors and interconnections required in the feedback loop around the input amplifier.

With reference to the logic diagram of Fig. 5, operation of the A-to-D converter is as follows.

The counter is a modulus 3000 counter, which is used to provide qualifying signals to the control logic as well as to help perform the analog-to-digital conversion. The counter is counting at time t_0 and the control logic maintains the autozero mode until the counter reaches the point at which either 159 or 1590 counts are left before it resets, depending on whether the range requires the short integration time (159 counts) or the long integration time (1590 counts). The integrator is then connected to the input amplifier and the integrator output ramps either up or down, depending on the polarity of the input signal.

When the counter reaches 3000 counts, the comparator output is sampled to determine whether the positive or negative reference voltage is to be connected to the integrator to return the output voltage to the starting level. When the comparator output is negative, the integrator output voltage goes in a positive direction when the reference voltage is connected, and the minus sign appears in the display. If the comparator output voltage is positive, the integrator output will decrease in a negative direction, and the minus sign will not appear.

When the comparator output voltage goes through zero volts and changes sign, the counter reading is tested for greater-than 1100 counts. If the

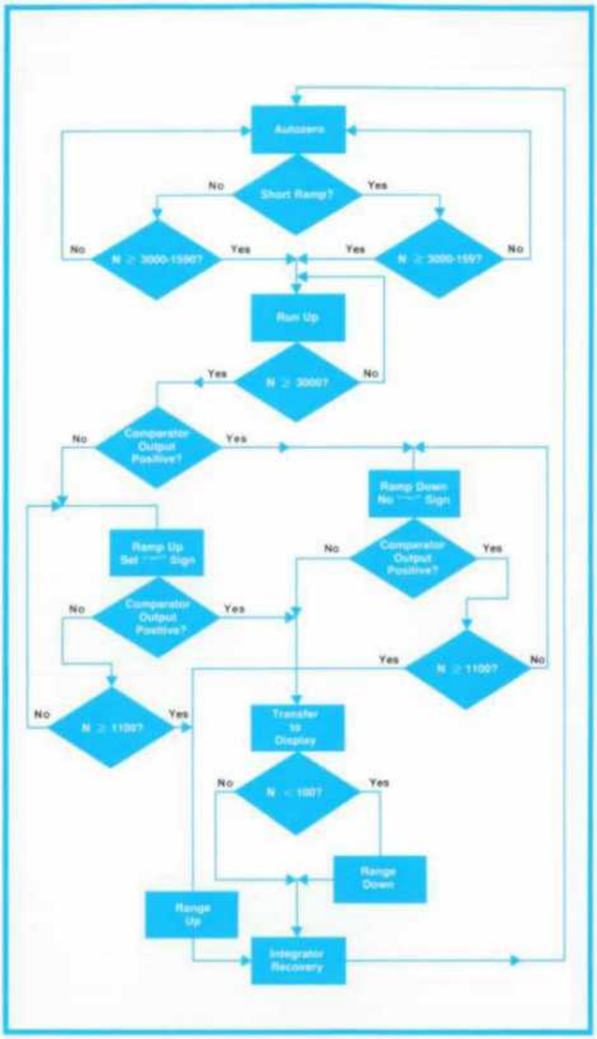

Fig. 5. *Flow diagram of control logic in Multimeter's analog-to-digital converter.*

counter output is greater than 1100 counts, the instrument is up-ranged one range and resequenced through an integrator recovery phase, to re-zero the integrator, and then sequenced to the autozero phase to repeat the measurement.

If the count is less than 1100 counts, the counter output is transferred to the display and is tested for less than 100 counts. If the count is less than 100, the instrument is down-ranged one range, and resequenced through the integrator recovery and autozero phases.

Multimeter Operation

Ac voltages are rectified to derive a dc voltage proportional to the average value of the ac waveform calibrated to the rms value for a sine wave, and the resulting dc voltage is applied to the integrator. To minimize the size of the filter capacitor

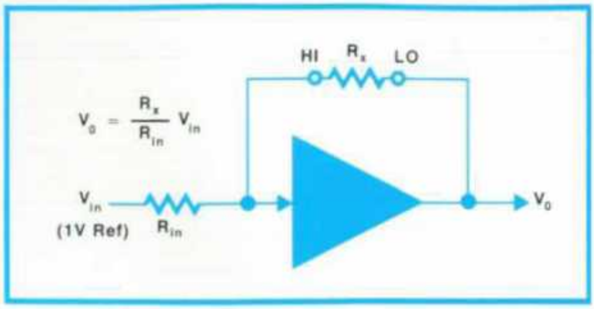

Fig. 6. *Input configuration for resistance measurements.*

C3, full-wave rectification is used. This is accomplished with inverter A3, which overrides the output of A2 on positive-going signal excursions at its output.

Resistances are measured by supplying a 1-volt reference signal to the input amplifier through a range resistor and configuring the amplifier to place the unknown as the feedback resistor, as shown in Fig. 6. The amplifier output is proportional to the ratio of the unknown resistance to the range resistor.

To protect the ohms circuit from inadvertant application of an external voltage, a series resistor protects the input and it also acts as a fuse for voltages greater than 130 volts. This resistor is clip-mounted to the circuit board so that it can be replaced easily without soldering.

Power Supply

A single 10-volt battery pack supplies all power for operation of the multimeter. Positive and negative reference voltages are established by tying the ground to a tap in a resistive divider that spans the battery (Fig. 7). Actually, three ground reference points are established: (1) analog circuit ground; (2) logic circuit ground; and (3) LED display ground. Separation of the analog circuit ground from the other grounds is necessary to prevent digital circuit transients from interfering with operation of the analog circuits, and to provide proper voltages for MOS switching.

As shown in the diagram, the analog and logic grounds are isolated from the resistive divider by operational amplifiers that provide low impedance sources for the ground circuits. The voltage across the resistive divider is maintained constant through all useful levels of battery charge by a zener diode with a thermistor providing compensation for the temperature characteristics of the zener. If the zener voltage should drift with age, it can be compensated for with the potentiometer provided. This is the only circuit adjustment required in the entire instrument.

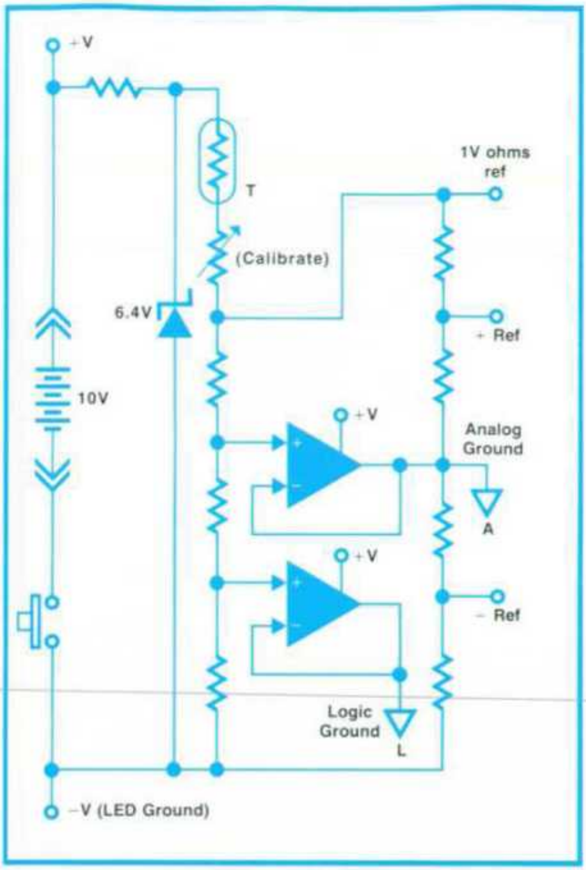

Fig. 7. *Power supply isolates analog circuit ground from other grounds to minimize coupling of transients.*

The LED display circuits work directly from the battery. As the battery charge depletes, the LED display dims and finally becomes unreadable, indicating that the battery needs recharging. The accuracy of readings is affected by only 1 or 2 counts in the least significant digit when the battery level is too low for a readable display, so this is a practical way to indicate the need for battery recharging.

Putting It All Together

Circuit simplification was a key factor in making the Probe Multimeter feasible. One step taken was to do as much digitally as possible because digital circuits can be implemented very inexpensively. For example, digital comparison, rather than analog comparison, is used to trigger autorange changes.

As much of the circuitry as possible was put on one monolithic integrated circuit, a 150 × 170 mil chip (3.9 × 4.3 mm) made by an N-MOS process developed for the 4096-bit ROM's used in HP calculators. This chip (Fig. 8) includes the counters, buffer storage, code conversion for the display, display scanner, autorange circuits, several ROM's that store the programs needed to operate the multimeter (approximately 3500 bits are stored in ROM), and most of the analog switching.

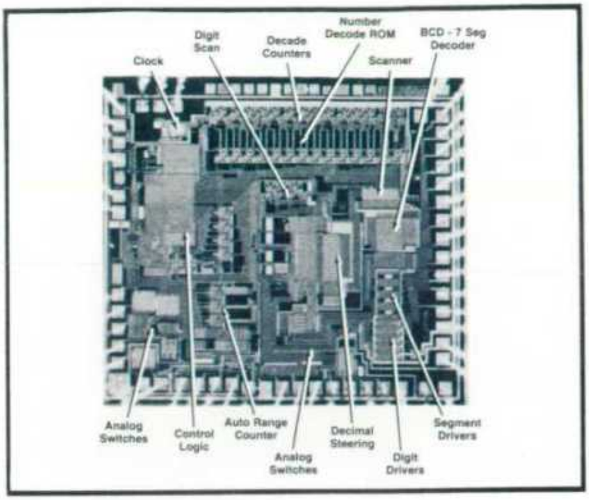

Fig. 8. *As much of the circuitry as possible was placed on one custom-made monolithic IC chip. This chip has 40 flip-flops, 19 MOSFET switches and about 3500 bits of ROM.*

A distinct advantage of placing all of the digital circuitry on a single chip is the large reduction in the number of interconnections required. This is particularly true in the case of the analog switches required for the analog-to-digital conversion and autoranging. The simplified circuit in Fig. 9 shows how this is accomplished. All of the MOSFET gates as well as many of the sources and drains are connected internally on the MOS chip. Only three mechanical switches are required to operate the instrument: the power switch, function switch, and display invert switch. The remaining 19 switches are on the MOS chip.

As much as possible of the remaining circuitry was put on a 28 × 38 mm thin-film hybrid circuit (Fig. 10). This includes six operational amplifiers (three chips, each with two op amps), the comparator, one chip with the two input FET's, the bipolar current amplifier that drives the display, four diode chips (rectifiers and protection diodes), capacitor chips, high-value resistor chips, and tantalum-nitride thin-film resistors.

For resistors with values higher than is practical with this thin-film process (greater than 60k ohms), resistor chips bonded to the substrate are used if the value is not critical, e.g. a pull-up resistor. But where accuracy and stability are required, such as in the high-value range resistors, discrete resistors mounted on a circuit board are used. To minimize size and cost, resistors with accuracies specified within 1% were chosen, rather than the larger high-

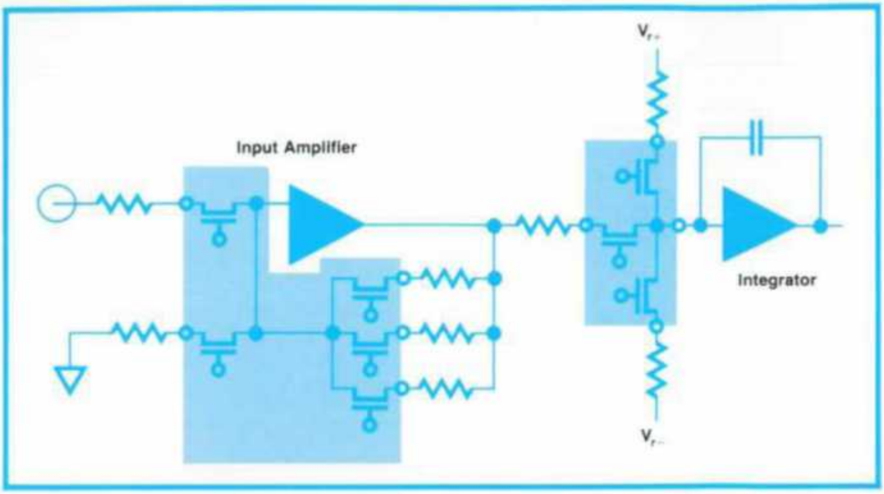

Fig. 9. Simplified diagram of the input amplifier and integrator input shows how MOSFET switches are used. Only ten external connections are required for eight switches.

precision resistors. However, a small-value thin-film resistor is in series with each of these resistors, and the thin-film resistors are laser trimmed to give the series combination the 0.1% accuracy desired. The thin-film resistors have a stability of 0.01% per year and a temperature coefficient of approximately −75 ppm/°C.

Resistor trimming on the thin-film substrate is accomplished by a computer-controlled laser trim system. The value of a tantalum-nitride thin-film resistor is increased in steps by opening selected gold shorting bars placed across small and medium size resistive segments of the resistor. By this method, a resistor can be trimmed in a few seconds to an accuracy of 0.01%. An entire circuit can be functionally calibrated by actively trimming resistors to compensate for parameters such as amplifier gain, input offset voltages, and so on. In addition to trimming resistors, the computer-controlled system pretests the substrate and printed-circuit board prior to trimming, and functionally tests the entire circuit after trim.

The printed-circuit board (Fig. 11) also holds the LED display cluster, large-value, high-voltage capacitors, power supply zener diode and its compensating thermistor, power supply trimmer pot, and the power switch, as well as the thin-film substrate.

Computer or calculator controlled tests are performed at various stages in the production process, beginning with evaluation of the MOS chip and finishing with evaluation of the completed instrument. These automated tests are far more thorough than would be economically feasible with manual point-by-point tests and are a major contribution towards the realization of quality at low cost.

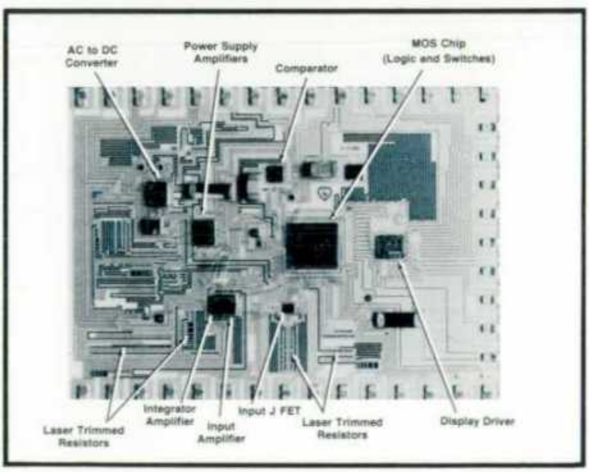

Fig. 10. *Thin-film hybrid circuit contains the stable, laser-trimmed resistors and also serves as a high-density interconnect for the other circuits.*

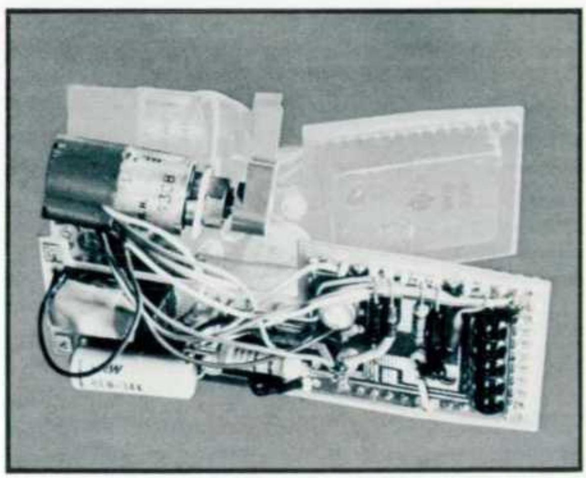

Fig. 11. *Thin-film hybrid circuit mounts on the back side of the printed-circuit board that holds discrete components. All of the multimeter's electrical components, except for the battery and the invert-display switch are shown here.*

SPECIFICATIONS
HP Model 970A Digital Multimeter

DC Voltmeter

RANGES: 0.1 V, 1 V, 10 V, 100 V, 1000 V, (500 V max input).
ACCURACY (20° C to 30° C):
±(0.7% of reading + 0.2% of range).
INPUT RESISTANCE: 10 MΩ, ±5%.
INPUT PROTECTION: ≤1000 V peak.
TEMPERATURE COEFFICIENT: ±(0.05% of reading + 0.02% of range)/° C.

AC Voltmeter

RANGES: 0.1 V, 1 V, 10 V, 100 V, 1000 V (500 V rms sine wave max input).
RESPONSE: Responds to average value of input waveform; calibrated to the rms value for sine waves.
ACCURACY (20° C to 30° C):

Ranges	45 Hz to 1 kHz	1 kHz to 3.5 kHz
1 V to 1000 V	±(2% of reading + 0.5% of range)	±(3% of reading + 0.5% of range)
0.1 V (>3 mV)	±(2% of reading + 0.5% of range)	±(5% of reading + 0.5% of range)

INPUT IMPEDANCE: 10 MΩ (±5%)//<30 pF.
INPUT PROTECTION: ≤1000 V peak.
TEMPERATURE COEFFICIENT: ±(0.05% of reading + 0.05% of range)/° C.

Ohmmeter

RANGES: 1 kΩ, 10 kΩ, 100 kΩ, 1000 kΩ, 10,000 kΩ.
ACCURACY (20° C to 30° C): (±1.5% of reading + 0.2% of range).
INPUT VOLTAGE PROTECTION (resistor fused): ≤115 V rms for up to 1 minute, ≤250 V rms for up to 10 seconds.
TEMPERATURE COEFFICIENT: ±(0.05% of reading + 0.02% of range)/° C.

General

A/D CONVERSION: Dual slope.
RANGING: Automatic.
SAMPLE RATE: 3/second.
OVERRANGE: 10%.
OPERATING TEMPERATURE RANGE: 0° C to 40° C.
POWER: Rechargeable batteries.
TYPICAL OPERATING TIME (fully charged battery): 2.5 hours continuous at 25° C.
TYPICAL BATTERY CHARGING TIME: ≥14 hours. (Indefinite charging will not damage battery.)
WEIGHT (with battery pack): 7 oz. (200 g).
DIMENSIONS: 1¼ in. x 1¾ in. x 6½ in. (32 x 45 x 165 mm).
PRICE IN U.S.A.: HP 970A, $275.
Extra Rechargeable Battery Pack: $25.
MANUFACTURING DIVISION: LOVELAND DIVISION
815 Fourteenth Street, S.W.
Loveland, Colorado 80537

Acknowledgments

The circuit design team consisted of Paul Febvre, Harlan Talley, Joe Marriott, Harry Heflin, and the authors. The mechanical design was accomplished by Dave Brown, Paul Febvre, Don Aupperle (industrial design), Gary Peterson, Roy Buck, and Bob Slutz.

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The authors are indebted to Bill Beierwaltes, Marketing Coordinator, and Dick Moore, R&D Manager, for many helpful suggestions.

References

1. A. Gookin, "Compactness and Versatility in a New Plug-Together Digital Multimeter," Hewlett-Packard Journal, August 1972.

Fig. 12. *Model 970A Digital Multimeter is supplied in a kit that includes a belt-mounted carrying case and a sunshade in addition to the three probe tips and battery charger. The battery pack (lower left) is shown here removed from the instrument.*

Virgil L. Laing (Right)

Fresh out of the University of Minnesota with bachelor's, master's, and PhD degrees in electrical engineering, Virgil Laing went to work for the Loveland Division's IC department in 1968, subsequently becoming project leader for developing the N-MOS process for the 4096-bit ROM's used in the 9800-series Calculators. Transferring to instruments, he designed a major part of the N-MOS circuitry in the Probe Multimeter and later became group leader for probe products development. An outdoor sports enthusiast, Virgil also enjoys hiking and camping with his family and pheasant hunting with his two German Shorthair Pointers.

Robert L. Dudley (Left)

Among the many products Bob Dudley had project responsibility for since joining HP in 1959 are the 690-series Microwave Sweep Oscillators, the 3300A Function Generator, and the 3469A Digital Multimeter. As a group leader, he was also involved with the 204C and 209A Oscillators, the 3310A Function Generator, and the 970A Probe Multimeter. At present, he is section manager in charge of basic instruments. Bob obtained a Bachelor's degree in Engineering Science from Brigham Young University and later under the HP Honors Co-op program, an MSEE from Stanford. He enjoys golf and goes skiing on water or snow. He's also been president of the Loveland Optimist Club, regional music leader for his church, as well as a high council member, and student-activities chairman of the IEEE Denver section.