1977

Analog tests: the microprocessor scores

Benefits derived include simplicity of measurements, use of cheaper components, and worthwhile results from "meaningless" data

The complexity and cost of making analog measurements can be reduced by the use of a microprocessor. In an analog instrument, the microprocessor not only can absorb many digital control functions, but it can also reduce analog circuitry drastically—if new analog techniques that take advantage of the microprocessor's power are utilized. Reducing the analog portion of the instrument is important, even at the expense of adding more digital circuitry, because precision analog components are expensive and adjusting, testing, and troubleshooting analog circuits is costly. Often, digital circuits can replace analog circuits because various functions can be executed in either mode. By using a microprocessor, many of these functions can be programmed in software rather than executed in hardware, either analog or digital.

Major ways in which microprocessors are reducing the cost and complexity of making analog measurements include the following. They permit sequential control logic to be replaced by stored control programs. They eliminate the need for certain auxiliary equipment by handling interfacing, programming, and other system functions. They give wider latitude in the selection of measurement circuits by making it possible to measure one parameter and then calculate another parameter that may be of interest. They reduce accuracy requirements by storing and applying corrections. And they permit meaningful results to be obtained from "meaningless" data. For example, measurement of the voltage across a resistor of unknown value carrying an unknown current is meaningless. But if that measurement is combined with a second measurement of voltage across a resistor of known value in series with the unknown resistor, useful information is obtained.

Maximizing microprocessor benefits

Early microprocessor-based instruments were designed with the prior art of the instrument–minicomputer combination in mind. Automatic test systems, for example, had been built for several years prior to the arrival of the low-cost microprocessor by combining a digital-output, programmable, analog-parameter measuring instrument with a minicomputer. The instruments involved were also capable of being used by themselves as manually set and read devices. Thus, the computer was not influencing how the measurements were being made but was only telling the instrument which measurement to make and then operating on the results of that measurement.

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Basic components of the GR 1657 Digibridge. The portion of the instrument's circuitry shown at the center consists of the microprocessor, a RAM, and a ROM. The signal paths shown in blue are periodic signals; those in red are control signals; and those in green are data signals.

Using the microprocessor in the same way the computer was used—as an "added-on" device to operate on the results of a measurement—resulted in instruments with important new features, and generally with new, higher prices. Real price–performance improvements did not occur until the microprocessor was truly integrated into the instrument. Designing such an instrument was a challenge to the instrument designer, who had to forget the complex methods with which he was familiar and go back to measurement fundamentals. He had to use the microprocessor not just to control the measurement but to change the *way in which it was made.* He had to simplify the instrument so that all of its costs, including parts and labor, could be reduced.

Benefit no. 1: new features

New, added features resulting from the use of the microprocessor are not the main subject of this discussion. However, they should be mentioned because, if such features are required, using the microprocessor inside the instrument to get them can save many dollars worth of added external equipment. In such applications, this can be the most important cost-saving use of the microprocessor. On the other hand, if such features are not needed, adding them only increases costs and complicates the use of the instrument.

One of the most important features microprocessors make possible is the improved interfacing with other equipment in systems applications. The microprocessor can reformat data and handle hand-shaking operations for proper transmission. It can save the cost of expensive interface boards by using more software and less hardware to do the same job.

Instruments have to interface with people too, and many microprocessor-based instruments display much more information than just numerical results. Flashing error messages, warnings, instructions, and other supplemental information can be of real value.

Several new microprocessor-based instruments are capable of being programmed to make simple measurement routines, but none, as yet, has the programming capability of even the simplest minicomputer-based systems. However, there are many applications where such simple programming will suffice. Thus, the microprocessor can replace an external minicomputer in some instances.

A simple example of rudimentary interfacing and programming is the multilimit component-sorting system shown in Fig. 1. Many such systems are in use today, both with automatic handlers and with people doing the mechanical function of inserting and disposing of the separate devices tested. Several digital comparators are required, each of them "programmed" to a specific limit and their outputs "interfaced" to give the person or handler a specific command (where to put each component tested). In the past, if many categories or bins were required, it was often less expensive to replace the necessary comparators with a minicomputer that could handle any reasonable number of limits easily. New microprocessor-based impedance-measuring instruments now do multilimit testing by themselves. The dollars saved are considerable.

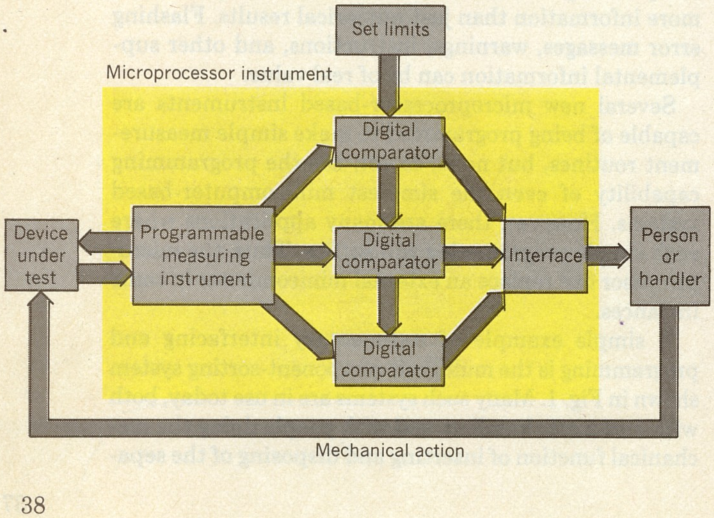
Benefit no. 2: cheaper measurements

Microprocessor-based instruments can take the results of the simplest measurements, transform them by calculation, and display desired parameters that would be much more difficult to measure directly. For example, a conventional counter measures the period of a low-frequency signal much more accurately and faster than it measures its frequency—but the operator then has to take the reciprocal to obtain frequency. "Reciprocating" or "computing" counters have been developed, but they require extensive digital circuitry to make the division. With the microprocessor, the calculation is easy.

Resistance and conductance are also reciprocals. A D/A based bridge can balance much faster if the fast current output of the D/A is tied directly to the detector. The easiest circuit configuration employing this advantage measures conductance rather than resistance. With a microprocessor instrument, the conductance measurement is easily translated into a resistance value.

Yet another example is ac impedance, which can be expressed in many parameters—complex impedance or admittance, or as various combinations of effective series or parallel R, C, or L, or one of them and Q or D (dissipation factor). Some combinations are easier to measure than others, particularly if they are to be measured automatically. The Boonton Electronics Corporation's 76A 1-MHz capacitance bridge, for example, measures parallel C and G, the easiest combination to measure. The user can utilize this combination, or have the microprocessor in the instrument calculate series capacitance and D, Q, or series resistance. Without the microprocessor, these results would have required different circuit configurations to get the various combinations of parameters. The GenRad 2230 component test system goes even further. Its impedance-measuring module measures parallel C and G, but it also calculates inductance and Q as well as the various other capacitance-loss combinations. To do so, the bridge has to balance for negative capacitance ($C = -1/\omega^2 L$), a simpler task than having a different circuit configuration to measure L.

[1] In a modern system for limit sorting of electrical components, a microprocessor replaces many of the components required to give an indication of sorting-bin number. It can also add features such as a percent-deviation display.



In all of these examples, the microprocessor is not used to provide new measurement methods. Rather, it merely allows the choice of the easiest method and requires only one measurement circuit to get various results. More generally, one quantity can be measured in terms of another, or several others, of completely different dimensions and the desired result calculated. Power can be calculated from measured voltage and current or capacitance from resistance and time.

Benefit no. 3: calibrations allow cheaper parts

A calibration correction normally is used to improve the accuracy of a measurement already made. It does not affect how the measurement was made. But if a calibration, or systematic error correction, improves the accuracy of the measuring device, then in order to get a specified accuracy, a simpler, less accurate device could be used. Using a microprocessor to store error-correction information, and apply it, means that the microprocessor can simplify analog circuits as well as ease instrument component-tolerance requirements, and thus eliminate the need for some adjustment controls.

Decreasing the time intervals between calibrations increases the number of different error sources that are corrected and increases the amount of hardware saved. Table I illustrates these relationships, and shows, as well other characteristics of four types of calibrations categorized by their intended recalibration time intervals. It is worth noting that the error sources listed in Table I are somewhat analogous to noise, and that calibrations, or corrections for these errors, provide a function comparable to that of a filter (a high-pass filter that rejects low-frequency noise). A microprocessor can make very rapid error corrections and thereby permits the use of less stable, higher-drift, noisier components. Such rapid error correction can even eliminate the need for conventional filters.

Perhaps the most important "calibration" is the "zero" correction, particularly for low-level measurements. Some years ago, most electronic instruments had panel zero adjustments. These were eliminated with the advent of analog automatic zeroing circuits that stored the result of a zeroing measurement in a capacitor and subtracted it from successive measurements by means of a differential amplifier. Next came zeroing circuits, in which the correction was stored as a preset value in a counter, usually part of a dual-slope converter, and subtracted when the actual measurement count was made. These techniques required extra circuitry. If a microprocessor is already a part of the instrument, the microprocessor can store and subtract at virtually no added cost.

Once the "zero" is established, one more calibration is adequate to determine the response of a linear detector. This calibration is the scale factor or slope calibration and is usually made near full scale for best accuracy. A standard is required and every instrument has its internal standard—a voltage, resistance, frequency, etc.—that can only be checked by some external standard. Although it

I. Types of calibrations or error corrections by time interval

Time Interval	Type of Standard	Source of Calibration	Cause of Errors Corrected	Stored Microprocessor Calibration Replaces
Years—permanent	External	Manufacturer (initial, repair)	Component values Gross offsets ("dc" noise)	Tight-tolerance components, low-offset op amps, trimmers
Months (regular calibration cycle)	External	Users' calibration labs	Aging drifts (extremely LF noise) plus above	Long-term, stable components, trimmers, low-drift op amps, plus above
Minutes, hours (during use)	Internal	Operator or automatic	Offset voltage drifts ("warm-up drifts, temperature changes—VLF noise) plus all above	Panel adjustments, stable components, low-tolerance components
Milliseconds, seconds (every few measurements or every measurement)	Internal	Automatic	"Fast drift" or LF noise plus all above	Filters, plus all above

used to be a manual adjustment procedure, this calibration now is automatic. It requires a multiplication or division, which can be handled quite precisely by a D/A converter or dual-slope integrator but can be done even better by a microprocessor. Like the zeroing procedure, it can be carried out for every measurement if desired but that is usually not necessary.

Most instruments have several ranges and in different kinds of instruments there are different kinds of ranges. They may be a set of standards (bridge ratio-arm resistors) or a single standard with some precision scaling device (precision resistor divider or a digital frequency divider). Unless this division is absolute and permanent, it too should be calibrated, but it is not necessary to do so for each measurement. One example of an instrument that makes such calibrations is the John Fluke Manufacturing Company, Inc., 8500A. It not only stores corrections for each range, but also gives a warning when the ranging resistors are outside a reasonable tolerance and thus of suspect stability. And it also pinpoints the component that is the culprit. Such self-diagnosis should save service costs and reduce substantially the portion of "down time" that is devoted to diagnosis of the problem.

The microprocessor really shines when the detecting device is nonlinear. It can interpolate between stored corrections or adapt them as constants in some characteristic formula. Such calibrations would allow the use of less expensive, nonlinear detector circuits even for precision measurements.

One example of a nonlinear device can be the transducer. If it isn't linear, as is often the case, the microprocessor can evaluate the algebraic expression for the transfer function of the transducer. If no algebraic expression is available, the microprocessor can store enough information to obtain a precise result by interpolation. The microprocessor thereby permits the use of simple transducers and measurement circuits and provides greater flexibility since a common measurement circuit can be used with many transducers, and the nonlinearity of each one corrected separately.

Benefit no. 4: simpler measurement methods

In the previous discussion, the microprocessor's memory and calculating power were used to operate on the results of some measuring device. It permitted the choice of the measurement circuit or improved the results, but the basic measurement methods were those used previously. There are other applications where the microprocessor doesn't sit and wait for results, even though it may be controlling the process, but goes in and gets data needed to obtain the result. Such applications have two basic features: they all require more than one measurement for every good result and each separate measurement is meaningless by itself. With these conditions, there is no useful result until the microprocessor acts on the raw data.

A simple example of a meaningless measurement is the measurement of the voltage across a resistor of unknown value carrying an unknown current, as mentioned earlier. This one measurement reveals nothing. To measure the value of the unknown resistor, a resistor of known value (a standard resistor) is added in series with the unknown and the voltage across the known resistor is measured. Then the ratio of two voltages is determined, which is also the ratio of the two resistances. If a new unknown resistor is to be measured, the current is changed and a new measurement across the standard resistor, as well as the unknown resistor, is required. (This differs from a calibration, if we consider a calibration as a correction that can be applied to more than one measurement.) If, however, a precision current source and precise voltmeter are used, the single measurement of the unknown resistance is a good measurement of resistance. This technique is used in most digital voltmeter measurements. The Julie Research Laboratories, Inc., DM1000 puts a standard resistor in series to calibrate the system occasionally but this calibration measurement is not required for each measurement of a new unknown value. In the two-measurement method, the measurement of *IR* is required for each measurement.

The voltmeter two-measurement method just described can be implemented in two ways. Two voltmeters may be employed or one voltmeter may be switched to measure both voltages successively. The technique of using two voltmeters that make measurements at the same time has the advantage of being independent of current variations. It has the disadvantage that the calculated ratio depends on the ratio of the sensitivities or scale factors of the two voltmeters. If a single voltmeter is switched, however, it need not be accurate, though it must be linear and have adequate resolution. It need only

II. Comparison of R, L, C measuring instruments

Type	Basic Accuracy	Parameters, Frequency Display	Ratio Device	Intro-duction Year	Rel-ative Price
Manual bridge	0.1%	R and G dc; $C_S C_P$, L_S, L_P, D and Q 1 kHz $CGRL$ digital, D and Q dial	Decade resistor	1970	1.16
Automatic bridge	0.1%	C_S, L_S, R_S, D 120 Hz, 1 kHz All digital	Precision D/A	1970	6.9
Digital meter	0.1% 1 kHz 0.5% 120 Hz	R dc, C_S, L_S, D, Q 120 Hz, 1 kHz RC and L digital, DQ dial	Dual-slope integrator	1974	3.8
Microprocessor meter	0.2%	R_S, R_P, C_S, C_P, L_S, L_P, D and Q 120 Hz 1 kHz All digital	Microprocessor calculations	1976	1.0

be stable during the time of the two measurements. For a digital implementation, any A/D converter using 10-percent components would be adequate as long as it were linear. It need not be something one might reasonably call a digital voltmeter. Moreover, if a fast A/D is used, the current and the A/D need only be stable during the time of the measurement, usually well under one second. This "one meter" method is a substitution method, the basic technique of precision measurements. It can give high accuracy using simple circuitry.

The GR 1657 Digibridge is a new microprocessor-based instrument that uses the one-meter method. The "meter" or A/D must be replaced by a phase-sensitive detector and converter combination because, for ac complex impedance, the vector components of the signals are required. The circuit used is a dual-slope converter whose "up" (sampling) slope is the integral of a series of half-wave samples of the ac signal and is proportional to that component of the signal in phase with the sampling pulses. The "down" measuring slope is the integration of an auxiliary direct current and is thus linear, as it must be for proper dual-slope operation. The dual-slope integrator takes a ratio, but it is not the ratio of two measured ac signals. It is, instead, the ratio of a component of one ac signal to a direct current. Because the calculation required to get useful results uses a division, the direct current cancels, as does the value of the integrating capacitor and other component values. Even the sampling time need not be precise as long as it is constant.

A basic difficulty in previous ac impedance meters has been in obtaining the proper phases for the reference or sampling signals. Usually, two square waves are required that are precisely in phase and in quadrature with a specific sinusoidal signal. These square waves are difficult to get precisely, particularly if the ac signal from which they are derived is not of constant magnitude. As a result, instruments using this system tend to have relatively poor phase-angle accuracy. With complex division, on the other hand, these references do not have to maintain any fixed phase relationship with respect to any analog signal because the ratio of two complex numbers depends only on the angle between them and not on their angle with respect to the reference coordinates. The references may be derived from any synchronous signal. In the GR 1657, all signals are derived from a single, HF crystal oscillator. This type of complex division would be impractical without some sort of calculator.

How much does the microprocessor save?

To see how the complexity and cost of making analog measurements can be reduced by the addition of a microprocessor, similar instruments that do and do not use a microprocessor should be compared. To make a fair comparison, the microprocessor-based instrument should have no extra features. It should be a simple, basic instrument with no important new operational features (output interfacing, deviation display, etc.) so that it better shows how the measurement itself was simplified. The GR 1657 is a good candidate for comparison because it is intentionally designed as a low-cost, no frills instrument. It uses the microprocessor directly in making the measurement and it has an ancestry of comparable instruments that do more or less the same job.

Table II shows four *RLC* measuring instruments with quite different measurement techniques. Basic accuracies and parameters are given. Relative prices are also indicated, normalized to that of the microprocessor-based instrument. The savings due to the microprocessor are substantial. For example, note that the automatic microprocessor meter costs less than the manually adjusted *CRL* bridge.

In the case of the GR 1657, part of the cost savings results from the use of fewer and less precise components. Due to the decrease in electrical components (and mechanical parts, as well), assembly costs are substantially less. The microprocessor-based instrument has no hand-soldered, wired connections, except in the power supply. Testing costs are reduced drastically since the microprocessor instrument has no adjustments of any kind. It either works or it doesn't work. Finally, if it doesn't work, troubleshooting costs are reduced because it is basically a one-board instrument (plus power supply and readout board) and is mostly digital, making it easy to test on an automatic circuit tester.

The example of cost savings in Table II was illustrated by a particular type of instrument, but the methods described could be adapted to instruments that measure many other quantities. The resulting cost savings could be just as dramatic.

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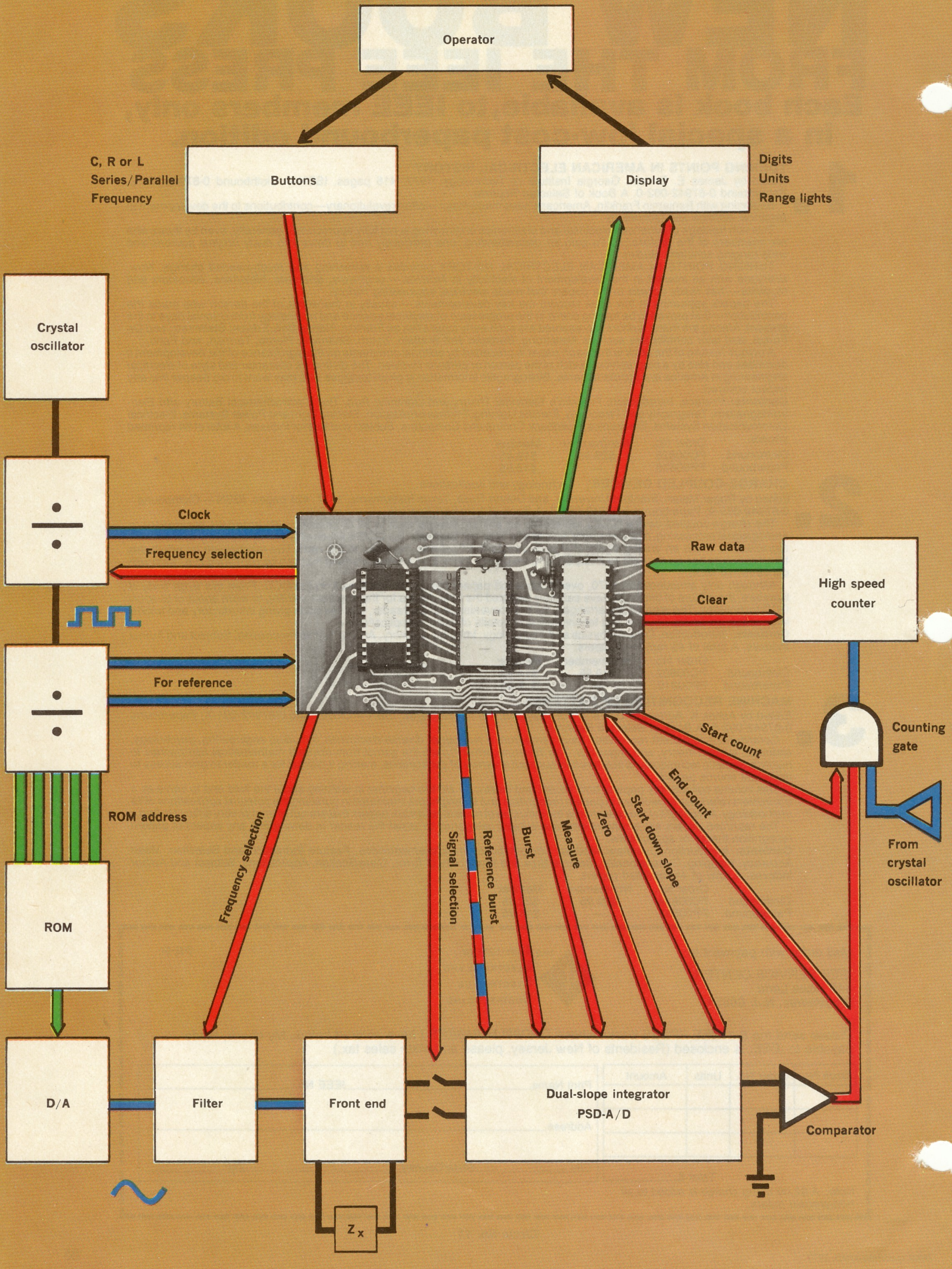
Operator
C, R or L
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Frequency
Buttons
Display
Digits
Units
Range lights
Crystal oscillator
Clock
Frequency selection
For reference
Raw data
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High speed counter
Start count
Counting gate
End count
From crystal oscillator
ROM address
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Frequency selection
Signal selection
Reference burst
Burst
Measure
Zero
Start down slope
D/A
Filter
Front end
Dual-slope integrator PSD-A/D
Comparator
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