VOLUME 11 □ NUMBER 11 IEEE spectrum NOVEMBER 1974

IEEE spectrum

articles

departments

The most expensive part of a computer isn't the computer anymore.

It's the people who work with it.

So Data General is introducing a family of medium scale computers that cut down on the work people have to do.

Eclipse.

You won't have to clean up the mistakes this computer makes. Eclipse has automatic memory error correction.

You won't have to rewrite complicated instructions every time you need them. Eclipse's microprogrammed architecture includes a comprehensive new set of instructions so powerful they do the work of entire subroutines.

You won't have to lose speed doing special subroutines with software. Eclipse has a Writeable Control Storage Unit that lets you keep them in the hardware.

You won't have to use assembly language to make your programs go fast. Eclipse is so fast it can run high level languages at assembly language speeds. (It has a bipolar memory cache that makes semiconductor memory a lot faster. Plus core and semiconductor memory interleaving for even more speed. And the fastest Floating Point Processor in the industry.)

And even though Eclipse is a brand new computer, you won't have to write a lot of systems software or jury-rig your peripherals. Eclipse is upwards compatible with the Nova line. So all the software and peripherals we've already made can go right to work on the Eclipse.

Write for our brochure. And see how bright an Eclipse can be.

DataGeneral

The computer company you can understand.

Data General Corporation, Southboro, Massachusetts 01772, (617) 485-9100. Data Gen of Canada Ltd., Hull, Quebec, J8Y3S6, Data General Europe, 116 Rue de la Tour, Paris 75016 France. Data General Australia, Melbourne (03) 82-1361/Sydney (02) 908-1366.

Circle No. 1 on Reader Service Card

the cover

We borrowed parts and ideas from Tektronix, Hewlett-Packard, Philips, Fluke, Biomation, and other manufacturers to build this portable, programmable, easy-to-operate, self-testing, auto-calibrating instrument that users say they want. It even displays its own operating instructions, as depicted in the top half of the CRT. One user, viewing the cover drawing, told us, "To get all the features I want, the instrument would extend another six feet." To be portable, said another skeptic, it would have to be mounted on one of NASA's rocket "crawlers." For more about our dream instrument, see page 69.

IEEE Publications Operations

IEEE SPECTRUM is published monthly by The Institute of Electrical and Electronics Engineers, Inc. Headquarters address: 345 East 47 Street, New York, N.Y. 10017. Cable address: ITRIPLEE. Telephone: 212—752-6800. Published at 20th and Northampton Sts., Easton, Pa. 18042. **Change of address** must be received by the first of a month to be effective for the following month's issue. Please use the change of address form below. **Annual subscription:** IEEE members, first subscription $3.00 included in dues. Single copies $4.00 Nonmember subscriptions and additional member subscriptions available in either microfiche or printed form. Prices obtainable on request. **Editorial correspondence** should be addressed to IEEE SPECTRUM at IEEE Headquarters. **Advertising correspondence** should be addressed to IEEE Advertising Department, at IEEE Headquarters. Telephone: 212—752-6800.

OTHER IEEE PUBLICATIONS: IEEE also publishes the PROCEEDINGS OF THE IEEE and more than 30 Transactions for IEEE Societies and Groups with specialized interests within the electrical and electronics field. Manuscripts for any IEEE publication should be sent to the editor of that publication whose name and address are shown on pp. 101–102 of the January 1974 issue of *Spectrum*. When in doubt, send the manuscript to E. K. Gannett, Publishing Services, at IEEE Headquarters, for forwarding to the correct party.

IEEE also copublishes, with the Institution of Electrical Engineers of London, England, *Electrical & Electronics Abstracts* and *Computer & Control Abstracts*, as well as their companion titles journals, *Current Papers in Electrical & Electronics Engineering* and *Current Papers on Computers and Control*.

MOVING?

PLEASE NOTIFY US 4 WEEKS IN ADVANCE

Name (Please Print) __________
Address __________
City ______ State/Country ______ Zip ______

MAIL TO: IEEE CODING DEPARTMENT
445 Hoes Lane, Piscataway, N.J. 08854

ATTACH LABEL HERE

- This notice of address change will apply to all publications to which you subscribe.
- List new address above.
- If you have a question about your subscription place label here and clip this form to your letter.

spectrum NOVEMBER VOLUME 11 NUMBER 11

spectral lines

Very safe systems pose dilemma

When the likelihood of catastrophic failure of a complex system is infinitesimal, the problem of protecting that system from such a failure assumes quite a different complexion from that associated with "everyday" (high-probability) failures. Such is the case with nuclear power plants, which, in the most authoritative study to date on the topic of accident risks in commercial nuclear plants,* are projected to yield risks of only one core melt accident per plant every 17 000 years. The consequences of a core melt accident depend on three factors: the amount of radioactivity released, the way it is dispersed due to prevailing weather conditions, and the number of people exposed. When these three factors in 4800 different combinations were assessed for the U.S. in the aforementioned study, the conclusions were: The probability of 100 or more fatalities is predicted to be about 1 in 1 000 000; the largest calculated value was 2300 fatalities with a probability of about one in a billion.

Nevertheless, despite the extreme unlikelihood of a specific fault occurring, the systems and safety engineers must provide instrumentation that will sense dangerous conditions and either provide an alarm to an operator or automatically trigger switchover to an alternate mode, including the possibility of emergency shutdown. The trouble with the former is that, considering the low probability that the fault in question has indeed occurred, a human operator may react to an alarm signal in disbelief, "freezing" while mulling over the strong probability that the signal may be false. On the other hand, the signal *may* be false, and permitting it to trigger a plant shutdown automatically could be economically disastrous or might even (if the power net back-up should prove insufficient) create serious hazards for blacked-out consumers.

This dilemma can apply not only to nuclear plants, but to large chemical plants. One notices a trend to larger plants, plants operating under more rigorous physical conditions, and plants dealing with more dangerous materials. An engineer for Imperial Chemical Industries, Ltd., observed that such trends mean that, in the event of a mishap, there is more energy to be released, more costly plant equipment that might be damaged, greater possible loss of production and/or materials, and the safety of the plant operators is at greater risk.

A technique that is simplistic in concept, if not in application, to combat the described dilemma is based on majority voting. In the ideal application of this technique, each critical process variable would be monitored by, say, three independent fault condition sensors. Any two, or all three, calling for a shutdown would cause actuation of the shutdown system; one would not. Refinements and elaborations of the technique are possible in which the majority voting is iterated, and in which signal lines leading from the sensors are brought to the voting equipment by different routes.

The application of majority voting to a complex, hazardous process is itself complex—and costly besides. Nevertheless, its use may provide not only a safer system, but one that is cheaper to operate because it is not shut down on false signals. On the other hand, there are reasons for resistance to the use of such high-integrity protective systems. The rationale goes like this: Because the primary unwanted hazardous events are extremely unlikely, nominal precautions are adequate. Furthermore, the design and installation of complex safety systems may be viewed by segments of the general population as an overt admission that serious hazards do exist. Management, sensitive to the possibility of stirring up consumer advocates in areas that managers themselves deem of little consequence, may foster secrecy or institute public relations programs of a defensive nature, or, more commendably, companies or entire industries may embark upon comprehensive (if costly) educational programs aimed at the general public.

Among proponents of these options and others, however, those supporting the view that the public cannot comprehend the complexities of nuclear and other potentially hazardous plants may be unknowingly propagating insidious side effects. They could, for example, engender an environment of secrecy among those engineers and technologists who are directly concerned with designing the protective systems. This could deter the interchange of valuable ideas among companies and from one industry to another.

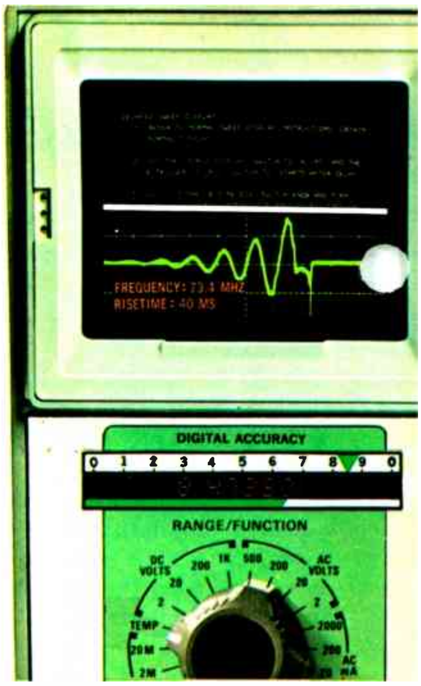
A recent positive event was a conference sponsored by the Engineering Foundation on the topic of "Process design, operation, and control for safety and reliability." Participants included both those concerned with nuclear power plants and those concerned with hazardous chemical processing plants. The open interchange of philosophies and experiences among systems designers, reliability experts, managers, and insurance company and Government agency representatives was profitable, enlightening, and reassuring. One would hope that this type of meeting would be repeated, and that complete proceedings would be published promptly, their availability properly advertised. Surely there are arguments for careful editing of such a proceedings to excise ill-considered and/or ill-phrased sentiments. But advice that such meetings be "closed," and that proceedings not be published on the grounds that biased interests might excerpt self-serving portions for out-of-context dissemination seems self-defeating.

Donald Christiansen, Editor

* An Assessment of Accident Risks in Commercial Nuclear Power Plants (Wash-1400), commissioned by the U.S. Atomic Energy Commission and now circulating in draft form.

Special report

Instrumentation '74



A close look at the state of the art in test equipment reveals lots of progress, some problem areas, and the potential for exciting new measurement capabilities in future years through advances in technology and design.

Instrumentation I

Looking ahead

Optical fibers, and tunable coherent sources and filters at infrared and optical frequencies, may key the future in test equipment

Every once in a while I am asked to dust off my crystal ball (single-crystal, of course) and discourse on the future of instrumentation, or what the Hewlett-Packard 1984 catalogue will offer. I always approach such an assignment with a great deal of trepidation because I am acutely aware of my limitations as a prophet and of the many unforeseeable discoveries that have occurred during my lifetime, that continue to occur, and that profoundly affect the course of our technology. But such excuses rarely dissuade my petitioners and so, at the risk of exposing myself to future ridicule, here are a few thoughts on what may lie ahead. But first let me back up a few decades and get a running start.

It is perhaps a truism to remark that electronic instrumentation exists in symbiosis with its market. The instrument maker must be sensitive to new research directions requiring new measurements. But these are generally the result of new discoveries that in themselves provide the techniques for building the new and better instruments that are needed. Thus, the destinies of the instrument maker are inextricably intertwined with those of the whole of today's technology. We grow as it grows and we contribute the tools for that growth.

Instrumentation's three revolutions

Since World War II, electronic instrumentation, together with the industry generally, has been through two revolutions, and is presently in the middle of a third. Roughly speaking, the fifties marked the transition from vacuum tubes to transistors, the sixties from transistors to integrated circuits, and the present decade from integrated circuits to large-scale integration. The first two revolutions have completely changed instrumentation; the third will do so again.

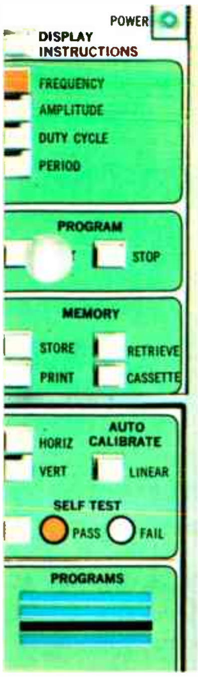
At first, the advent of the transistor seemed merely to require the redesign of existing instruments to achieve the improved performance, compactness, and reliability promised by the transistor. But it soon became evident, as transistor prices dropped, that the instrument price was no longer dominated by the number of active devices. New functions, new performance levels, new user convenience could economically be added with only one or two dozen more transistors.

With the advent of ICs, this latter trend became a stampede. Subassemblies that were formerly considered to be whole instruments became only minor parts of what were really integrated measuring systems.

The availability in a small space at low cost of hundreds of active elements opened the door to new design approaches. Active filters, A to D converters, digital filters, and the digital synthesis of frequencies became economical techniques and extended the dynamic range and precision of measurement.

Simultaneously, the appearance of the minicomputer made it practical to tie together into automatic measuring systems these more sophisticated instruments, each designed to accept digital programming

B. M. Oliver Hewlett-Packard Company



commands and to deliver digital data. Such systems, by eliminating high labor costs and human error, have revolutionized the production testing of everything from individual components to complete aircraft.

In addition, the computer coupled to D to A and A to D converters and to suitable displays has become an instrument in itself. Fourier transforms, auto- and cross-correlation of analog signals, power spectra, complex plane loci, once the province of the erudite academician, are now routinely measured by the structural engineer and the geophysicist. Pseudorandom noise tests made on equipment while in actual operation are no longer an intellectual speculation; they have become an essential technique for monitoring complex systems and automated processes.

Where do we go from here? Where will the LSI revolution take us? Certainly the past and present trend toward increased sophistication in instruments will continue, but probably with a new twist. Nowhere in the whole field of electronics has LSI had a greater impact than on the central processor of a computer or calculator. What cost tens of thousands of dollars in 1960, consumed kilowatts, occupied a full relay rack or more, and occasionally worked, now costs a few dollars, consumes milliwatts, resides on the outer few microns of a 5-mm-square silicon chip, and rarely fails. The cost of a modern computer or calculator is almost entirely in its bulk memory and input–output (I/O) devices.

Internally programmable instruments

But in an instrument most of the I/O devices needed are already present, and not much memory is needed to execute the relatively simple programs required to take a series of measurements. Thus, it appears likely that many future instruments will no longer be programmable only by an external computer. Rather they will have their own computer right inside.

The bewildering array of controls needed on some instruments appalls both the maker and the user. How much simpler and more convenient to enter all frequencies, gains, and other settings via a single keyboard as we now enter numbers in a calculator. Add a little memory and the device can carry out sequential measurements; then alter its internal configuration and make a different set of tests. Finally, internal programs can easily be recorded on magnetic cards for future use as is now done in desk-top and hand-held calculators. The day may not be far off when most of the instrument–user interaction will occur in natural languages.

Although a keyboard is an effective input device for an instrument, purely numeric readouts leave much to be desired. Alphanumeric displays add the possibility of greatly improved interaction through error messages, reminders to make certain initial tests or follow certain sequences, and through the display of the proper units. At present, alphanumeric displays are rather costly and limited in type font. For graphic and complex displays, we still must rely on the CRT with its attendant high voltage supplies, analog amplifiers, and other expensive circuitry. A low-cost replacement for the CRT would be a major breakthrough.

The optical-fiber data bus

While digital readouts are often used where old-fashioned analog readouts are much more convenient —watches, for example (I don't want to know that the time is 19:43, I want to know how long before the big hand points straight up), and voltmeters (just try to tune up an IF strip sometime, using an auto-ranging digital voltmeter)—there is no doubt that digital data is the natural language for intercommunication among instruments. This being so, the development of low-loss optical fibers may be very significant for the future of extended instrument systems and automatic process control. Developed for long-distance wide-band communication purposes, these tiny fibers, having only a few dB loss per kilometer, appear now to be the ideal data bus. They offer 100-MHz bandwidths, immunity from ground currents and induced interference, and complete independence from the logic levels used at either end.

Tunable coherent sources are beginning to appear in the infrared and optical parts of the spectrum. Tunable filters will soon be available; optical mixers already exist. It is quite possible that over the next decade or two instrumentation will cover this part of the spectrum as comprehensively as it now covers the microwave range. Whether this happens or not will depend primarily on the market demand, for instrumentation in the future, as in the past, will respond to new needs as they arise.

Bernard M. Oliver (F) has been vice president of research and development for Hewlett-Packard since 1957. He joined the company in 1952 as director of research after 12 years with Bell Telephone Laboratories where he worked on the development of automatic tracking radar, television transmission, information theory, and efficient coding systems. Dr. Oliver holds more than 50 patents in electronics and has written numerous technical articles. He was a Vice President of IEEE in 1963 and served as President in 1965.

The microprocessor: jack-of-all-trades

It's used for calibration, control, computation, conversion, decision-making, test, and maintenance

William G. Smith, an engineering manager at Hewlett-Packard, Loveland, Colo., says he can't think of one new instrument design in his shop that doesn't include a microprocessor. His civil engineering equipment group was among the first to start imbedding chip-sized computers in instruments. But, his experience is no longer an unusual one, for many new instruments built around microprocessors are beginning to appear on the marketplace. Engineers familiar with products now on the drawing boards seem to agree that the next two years will see a great outpouring of new, microprocessor-based instruments.

Reasons for this development are not hard to find. For one thing, microprocessors can fill applications where minicomputers may be too expensive. But, microprocessors are not just cheaper—if slower—substitutes for minicomputers. The most dramatic advance is that microprocessors, in the form of integrated circuit packages, are being mounted on circuit boards and incorporated—almost invisibly—into the instrument packages themselves.

While surveying the design of a dozen existing microprocessor-based instruments, this writer was impressed by the variety of instrument functions that seem to lend themselves to microprocessor implementation. This article examines some of these functions, using various features of existing instruments as examples.

Before we elaborate upon these functions a few words need to be said about general design considerations for microprocessor-based instruments.

A whole new ball game

As microprocessors become imbedded in more and more instruments, it is clear that users and manufacturers alike will have to adjust to a whole new instrument ball game.

Certainly, coping with software is a new experience for many instrument design engineers and users. But this is only the beginning. With the advent of microprocessors, more instruments than ever can be expected to move toward essentially digital operation. Several manufacturers and users are already pressing for the development of more sensors and transducers with digital outputs. Unfortunately, relatively few usable digital sensing devices are, as yet, available. There are also some very pleasant changes to which designers can look forward. For example, once a microprocessor-based instrument design is completed, the turnaround time for innovative changes and redesigns can be very fast.

Howard Falk Senior Associate Editor

When product planning people ask for a new feature to be added to an instrument—provided that feature can be handled by software—the engineering department can quickly put together a prototype for hands-on evaluation by their marketing group, and then quickly revise the design as needed. This can lead to more rapid and close-fitting agreement between marketing and engineering, with designs being more quickly and readily accepted for production.

However, there do seem to be some instrument problems that microprocessors may *not* be able to solve. As William Walker, Engineering Group V.P. at Tektronix Inc. points out, it is one thing to collect information and process it, but physical manipulation of instrument controls can sometimes be a difficult problem for the microprocessor.

Another current limitation on the development of microprocessor-based instruments is that the designers are not always well-equipped to do the job. Generally, the available designers are either hardware people, or software people, or pure instrument people. What seems to be needed is a combination of all three skills.

Despite such limitations, microprocessors do seem to be the instrument wave of the future, and the ways they are proving most important to new instrument designs may not always be obvious.

Microprocessors compensate and calibrate

One key—and somewhat unexpected—by-product of microprocessor use in instruments, is the rapid spread of automatic calibration techniques. With a microprocessor, calibration can be fast, convenient, and often more accurate than by manual techniques.

Compensation and calibration problems can also be approached in new ways. Parameters that change with shifting conditions of operation can be monitored by the processor. Then, instead of trying to compensate by controlling these operating conditions, or by shifting circuit parameters within the instrument, the output readings of the instrument can be directly compensated using correction values computed by the processor.

For example, several microprocessor-based instruments now in development use transistor amplifiers whose output is temperature-dependent. Instead of trying to compensate the circuitry for temperature changes, the processor can simply monitor ambient temperature and calculate compensation factors as needed. A similar approach is used in a cable-length test set at Bell Telephone Laboratories (Holmdel, N.J.). Here, a microprocessor monitors the frequency of a test oscillator and compares it to a calibration frequency. Deviations from the calibrated value are used to calculate the correct test-set readings.

A third example of computed output reading adjustments is provided by an electronic distance measuring instrument. This type of equipment was, in the past, corrected for changes in the atmospheric index of refraction by shifting the instrument's oscillator frequency. The HP-3805 electronic distance meter (Hewlett-Packard Co., Loveland, Colo.) now uses a constant-frequency oscillator. This microprocessor-based instrument computes corrected distance readings based on current atmospheric conditions entered into the front panel by the operator.

Automatic zero compensation is important in systems such as those for weighing. The zero-location output level in an electronic scale may be affected by temperature and line voltage, as well as such factors as dirt and moisture accumulating on the weighing platform.

The objective of zero compensation is to find a number (corresponding to a strain transducer output level) that will result in a display of zero, when no object to be weighed is on the weighing platform. In microprocessor-based automatic zero compensation systems, such as those used at the Toledo Scale division of Reliance Electric (Toledo, Ohio), the number used as a zero reference is continuously monitored by the processor. If this number changes—within predetermined limits—when no object is on the platform, these changes are compensated for by the microprocessor program. With this arrangement, a series of successive weighings could each conceivably be referred to a different zero level, depending on the zero-balance condition before the weighing.

In a similar manner, a microprocessor is used to zero-calibrate torque readings for threaded fasteners used in automobile assembly. In a system developed by PCS, Inc. (Flint, Michigan), the peak torque value is taken as each fastener is tightened into place. The computer reads the zero-offset and shunt calibration from the tool transducer, and true torque is then computed from the raw data.

Temperature-effect corrections are central design features in many kinds of instrumentation. With improved corrections, manufacturers can specify instruments over wider temperature ranges and, in some cases, improve the accuracy specifications of existing instruments.

Automatic analog temperature compensation has been available for some time, but the analog compensation devices tend to be complex and dependent on the level of the measured parameter as well as the temperature. Compensation of a variety of instrument levels and ranges by analog techniques is often impractical because of the difficulties involved in changing analog constants. In contrast, microprocessor calculation of a great variety of temperature corrections is a relatively simple matter, when stored tables of coefficients can be plugged into compensation formulas.

Calibrating large instruments

Some large, complex instruments are very difficult to calibrate. For example, it may take a technician as long as three hours to calibrate an instrument for measuring nuclear magnetic resonance. While instrument manufacturers could not justify the cost of installing minicomputers to calibrate such instruments, microprocessors now make this practical. The major calibration problem is that a sequence of adjustments must be reiterated in an attempt to make readings converge. When the sequence is long, the technician may have difficulty determining whether or not the readings are actually converging.

This is a situation that can be handled effectively with computer programs. Calculated results can cue the technician on whether he is going in the right direction, and could remind him of the best sequence of adjustments. Taking it a step further, the programs could be arranged so that the instrument operator turns on the calibration procedure when he leaves the laboratory at night. Then, when he returns in the morning, the operator would find his instrument ready to go, with optimum performance.

At the instrument control center

Our discussion of calibration and compensation techniques may give the impression that microprocessors are added gadgets used to embellish instrument designs. In fact, they are finding their way into the very center of instrument systems, and microprocessors can allow users unprecedented control over these systems. For instance, control over the conditions under which data is to be automatically collected can be very detailed. When a voltage reaches a certain

A plea for open-ended instruments

Some sophisticated instrument users—like Raymond Dessy of Virginia Polytechnic-Institute and State University—feel that microcomputer-based instruments should provide users with a way to alter the built-in programs. Prof. Dessy complains that some instrument manufacturers won't even tell their users what language they use to program their built-in processors.

He praises Edax International for an instrument design (its X-ray fluorescence machine) in which plug-in slots for programmable read-only memory (PROM) cards are made available to the user, along with unused push buttons on the control panel. These buttons can be used to direct the instrument's microprocessor to the available PROM locations. Thus, the user can generate his own programs, record them on PROMs, and use them via the front panel push buttons, and he has an open-ended instrument he can shape to his own special needs. After all, Dessy points out, any one manufacturer can't possibly think of all the application programs an instrument user might want. Even if the data acquisition portion of an instrument can be standardized, users vary widely in what they want to do with acquired data, how they want to format it, what correction factors they need, etc.

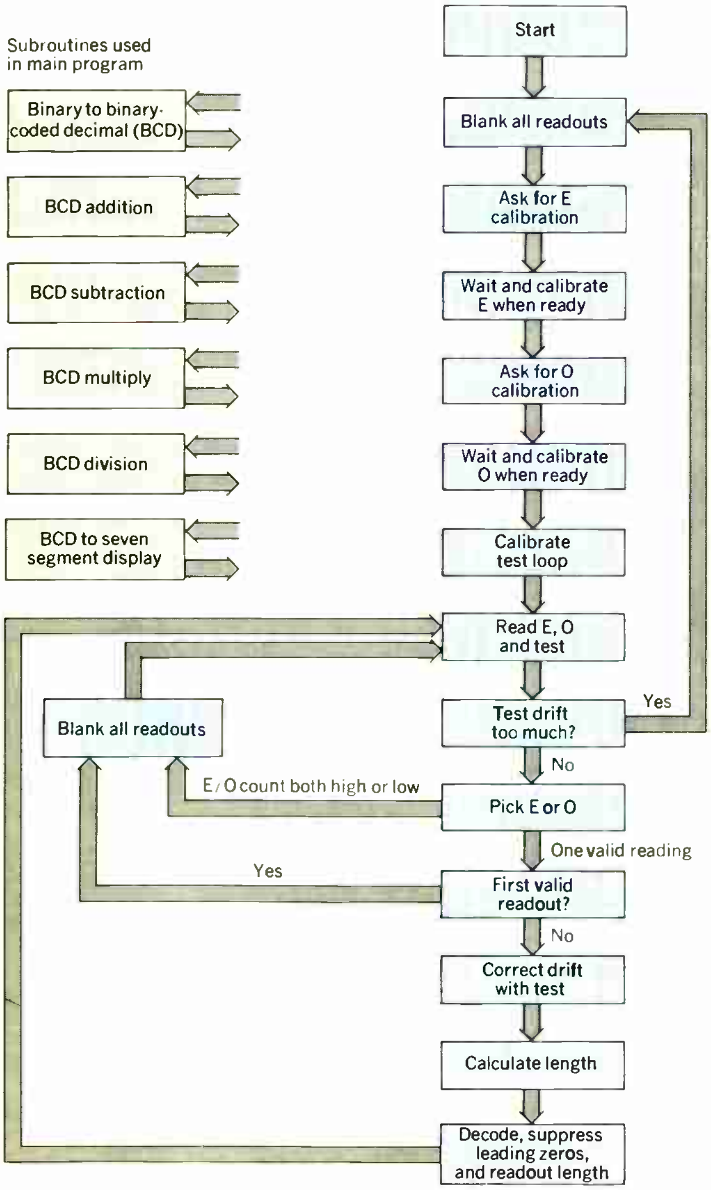
One of the beauties of the microprocessor-based instrument is that these things can be programmed.

If the instrument manufacturer takes the narrow view that his main benefit from the use of the microprocessors is to cut his development and production costs, he is missing out on an important user benefit: open-ended instrument capabilities.

level, or a count reaches a preset total, the microprocessor can cause the measurement to be taken, can store the measured value, and can wait for the same conditions to occur once more. Such detailed control would normally be impossible with manual instrument systems. In many cases, microprocessors can replace all the control functions formerly performed by hardwired logic and, at the same or an even lower cost, offer added computation capability.

As an example of overall instrument system control, consider the microprocessor program flow-diagram shown in Fig. 1. This program is used to control a Bell Laboratories cable-length test set; it carries out a complete, calibrated production test of an installed backboard cable.

[1] In this automatic cable-length test procedure, the cable is placed in the feed-back path of a digital oscillator. The longer the cable, the lower the natural frequency of the oscillator will be. One oscillator (E) is used for non-inverting twisted-pair cables; another (0) is used for inverting twisted-pair cables. A test loop containing a delay line is used for compensation. All necessary calculations are performed by the microprocessor.



When an instrumentation system is switched on, or restarted after a power interruption, a number of initial actions may be necessary. Active devices and timing circuits may need to be reset to their normal starting states, as do alarm indicators, and peripheral devices. With a microprocessor in the system, these actions can readily be taken care of by a power-on initialization program that controls and checks all needed functions.

Read-only memories (ROMs), used in conjunction with microprocessors, are opening up some new instrument control capabilities. By plugging in a particular ROM, the user can enter control parameters that might otherwise require him to set a large number of potentiometers and switches.

This arrangement is not as flexible as manual control. For example, with ten switches on an instrument panel, the user has many different combinations to choose from, and equal flexibility would require a very large number of ROMs. However, there are usually only a few combinations of settings that will be truly significant to the instrument user. Programmable ROMs (PROMs) provide even greater customizing capabilities. With these, the user can try out and implement his own instrument control arrangements, and the manufacturer can supply custom-selected instrument features.

In the Digitrend 220 data acquisition system (Doric Scientific Corp., San Diego, Calif.), a "configuration PROM" helps supply each instrument user with the specific feature he orders. Many different functions and features may be incorporated in this instrument by "burning" the proper bit-patterns into the PROM, and adding appropriate hardware if needed. Among the options controlled by this PROM are: selection of 60- or 50-Hz time base, programming of various data-input groupings, and alarm settings. Optional features available via the PROM include: autoranging, self-testing, symbol (as well as numeral) indication, decimal (rather than binary) control, automatic continuity-break detection, and a built-in clock and calendar. In addition, PROM-controlled functions allow the use of special scaling factors, computed linearization of measured quantities, and entry of fixed format data.

Microprocessors are well-equipped to manage such functions as automatic range selection in instruments, provided that the quality being measured is presented in digital form. For example, the Digitrend 220 system has four dc ranges from 10 mV to 10 volts. Range decisions are made on the basis of counts from the analog-to-digital (A/D) converter circuits. In the autoranging mode of operation, the first measurement is always made on the 1-volt range. The A/D count is taken, with range-change decisions—up or down—being made at 256, 2560, and 25 600 counts. In this instrument, the penalty for autoranging is a 2:1 loss of operating speed.

Control loops for slowly varying processes are difficult to implement with analog components, yet such loops are common in applications of process control instruments. With digital techniques, very long time constants can be easily implemented. For example, in a Hewlett-Packard microprocessor-based gas chromatograph, many slow feedback loops are controlled by software. Formerly, separate hardware was used for each loop, but now a single feedback routine—requiring about 50 words of memory—takes care of all of the loops under microprocessor control, and handles nonlinearities as well.

Microprocessors also offer the instrument designer an opportunity to make convenient use of the peripheral devices commonly associated with computer systems. With magnetic tape cassettes and floppy disk memories in the instrument package, the processor can be programmed to store large quantities of data for future use. The processor can also be used to keep records of the stored data, and to retrieve it conveniently.

Plotting devices, paper tape readers and punches, teletypes, and other keyboard devices can be interfaced to the microprocessor to make instrument systems more flexible and powerful.

In the H-P gas chromatograph, a microprocessor drives a printer–plotter, and software is used to perform all the necessary interface housekeeping, such as telling the peripheral device when to print a line or when to continue a line. By communicating with the printer–plotter only 80 times a second, the processor is able to control its operation.

Special-purpose instrument controls are relatively easy to implement in microprocessor-based instruments. These can allow extensive use of processor capabilities without requiring the user to use program-language instructions. Thus, the instrument panel shown in Fig. 2 allows the user to perform any of a number of mathematical operations on displayed data by simply pressing the appropriate push button. Selection of desired peripheral devices is also push-button controlled.

Making logical decisions

One of the principal features of the microprocessor-based instrument is often its ability to make logical decisions based on incoming data. Electronic weighing provides several examples of ways that microprocessor logical decision-making capabilities can be put to use in instrument systems.

After an object is placed on the platform of an electronic scale, and the weighing process is underway, the machine has to decide when the reading has settled to its final value. Here, the microprocessor must decide whether the incoming weight-data is varying significantly, or whether the variation is only random.

One of the legal requirements for weighing is that indications presented by a publicly used scale should always be accurate, within the tolerance limits of the instrument. The high-resolution data that comes directly from the strain transducers used in electronic scales forms a band of values, which has to be resolved into a single, correct value for display. By examining this data, microprocessor programs can use logical criteria to select the best display value.

A number of limits on overweight scale readings have been set by various local governments. One typical requirement is that a scale rated for 6 pounds maximum has to blank out if a 6½-pound object is placed on it. Similar requirements apply to value (the product of weight and unit price), which may be limited for both maximum and minimum readings. These limits can now be monitored and controlled in a flexible manner by microprocessor programs.

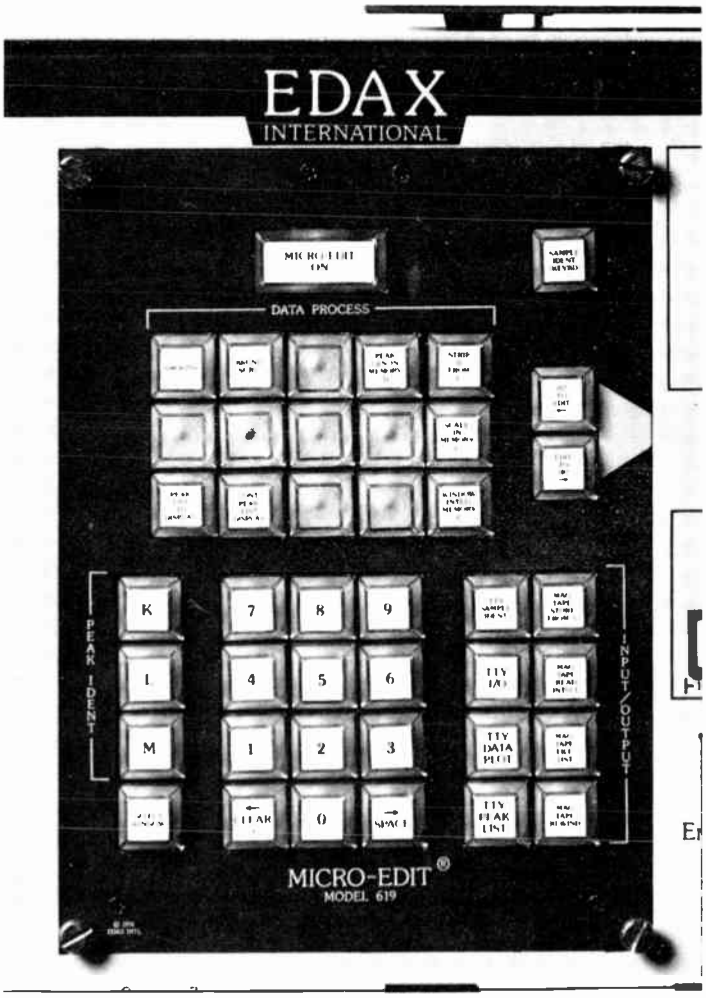
In electronic distance measuring instruments, there is a beam-break problem. The beam radiated by the instrument, and reflected back to it, may cross a highway or a city street, so people, cars, even birds can break the beam. When this happens, the instrument should be able to detect the fact that a break has occurred, put current readings in storage, and smoothly resume operation when the beam is reestablished.

In the microprocessor-based Hewlett-Packard distance instrument, break detection logic is implemented by a computer program. The instrument designers considered putting this function into hardwired logic, but found that, in addition to the cost of the added circuitry, its power consumption required would strain the power budget for this portable instrument.

Some of the versatility that microprocessor-based logical decision-making can give to an instrument is illustrated by applications of a system that uses digital line-scanning cameras, controlled by a microprocessor (Reticon Corp., Mountain View, Calif.)

Plywood grade—A, B, or C—is, for example, determined by counting the number of knots that appear on a 4- × 8-foot sheet, and noting the total area of the

[2] These push buttons control a microprocessor-based instrument for X-ray fluorescence spectroscopy. Both peripheral functions, such as tape storage or plotting, and mathematical functions, such as data-smoothing, are available in push-button form.



knots. This was formally done by an operator who counted and estimated, and then manually stamped the sheet. With microprocessor control, and a camera containing an array of photodiodes, the grading is now performed automatically.

In another application, silhouettes of logs in a sawmill are monitored by two, perpendicular photodiode-array cameras. Data from the images of the logs are then fed into the microprocessor, where a program decides where the first saw-cut should be made and how the log can be divided into various lumber sizes to obtain optimum yield. In a third application, o-rings on a conveyor belt pass a photodiode-array camera. Here, the microprocessor programs analyze the patterns of light and dark—corresponding to conveyor belt and o-ring material—to locate and measure inner and outer o-ring diameters.

In instruments like the H-P gas chromatograph, component parts of wildly complex graphical data must be interpreted. Areas and peaks of the data must be identified and sorted out. One peak must be separated from another and odd-shaped areas broken up for most efficient computation. All these decisions are now made, based on detailed logical criteria, by microprocessor programs stored in semiconductor memory (ROMs) inside the instrument.

Computation, complex but not too fast

In addition to logical decision-making, the analysis of data from instruments like gas chromatographs, and X-ray fluorescence spectrometers, requires a number of mathematical and statistical computations. For example, the Edax 707B analyzer (Edax International, Inc., Prairie View, Ill.) includes a microprocessor program that removes background information from X-ray spectra. The same program also removes data peaks that fail to meet a statistical, 95-percent confidence test. A proprietary digital frequency-filtering technique performs these functions. The program is quite complex and lengthy, taking 120 seconds to execute, according to the manufacturer.

Along with this background subtract program, the Edax instrument offers the user programs that subtract, or "strip," stored standard spectra from the spectra that are measured, while other programs scale the spectra so that peaks will overlap during this stripping process.

The microprocessor programs also allow the user to smooth his data, using a five-point least-squares program, so as to emphasize the smaller spectrum peaks. Using a "window" program, the user can integrate the peak data to get more accurate estimates.

A technique called liquid chromatography has recently become important in medical analysis—for instance, in getting fast diagnosis of drug overdoses. In liquid chromatography data from many spectrum scans is fed into an ensemble average that allows accurate analysis of trace components in the materials being tested.

At Virginia Polytechnic Institute and State University (Blacksburg, Va.), Raymond Dessy and his colleagues are using a microprocessor to do ensemble averaging at a rate of about 10 spectra per second. Their programs also monitor specific wave lengths, and collect absorption data, as a function of time, for those wavelengths.

An instrument-oriented microprocessor.

Many microprocessors tend to be 4-bit and 8-bit oriented because they grew out of calculator, point-of-sale terminal, and communications applications. The Intel, Rockwell, and Motorola machines, for example, all smack of the communications, calculator environment. They usually have character-oriented instruction sets, nice for handling numbers and letters. Some have binary-coded decimal characters, very appropriate for point-of-sale and calculator applications. After all, these are the areas where most of the sales are, right now, for microprocessor chips.

However, other microprocessor manufacturers, like Toshiba Digital Equipment Corp., and General Automation, Inc., are more oriented to the instrumentation and control market, where, the needs are typically quite different. Instrumentation processors need to be binary-oriented, with greater arithmetic and logic capability, and with enough interrupts to allow interaction with a fast external world—the classical instrumentation and control environment.

The Toshiba TLCS-12 machine includes such arithmetic hardware as add, subtract, multiply, divide, and-or, and exclusive-or. In addition, there are some nice bit-manipulation facilities. Individual bits in registers can be tested, cleared set, and handled separately. Not many machines offer that last capability, and it is very useful in control applications. For example, when building a programmable controller, the ability to manipulate individual bits is essential.

Another technique developed at V.P.I. uses solid-state gas detectors, manufactured by Figoera Electronica, a Japanese firm located at Shannon Airport in Ireland.

Five slightly different versions of these detectors were used to pick up five different sets of response characteristics from test samples. With these data, five simultaneous equations, each with five unknowns are set up, and solved by means of microprocessor programs. The answers reveal how much hydrocarbon, carbon monoxide, etc. is contained in the sample.

No chemist would go to the trouble of solving these equations by hand, but the V.P.I. people feel he would be delighted to push a button and get the answer he needs.

The Hewlett-Packard electronic distance measurement instrument, mentioned earlier in this article, uses its microprocessor to perform some simple statistical computations. In this instrument, each reading —taken in about five seconds—presents the average and variance of 3000 separate measurements. If this variance is larger than a predetermined value, an additional 3000 readings are taken and averaged in with the previous results.

All the mathematical computation is done by a microprocessor, but the measurements themselves are so fast that they are performed by hardwired transistor-transistor logic (TTL) circuits. These carry out 250 phase comparisons in every 60-ms interval. Each comparison requires that the instrument's transmitter frequencies be switched and gated. Comparison results are stored by gating microprocessor clock pulses (from a 200-kHz clock) into a software up-down counter.

Another microprocessor mathematical technique helps in handling noisy inputs by using software as a direct substitute for hardware filters. A number of different averaging procedures (algorithms) can be programmed for use with microprocessors. One of the advantages of these procedures is that, like other microprocessor programs, they can be put in ROM or PROM memory form and easily changed by instrument users. Equivalent digital or analog filter hardware would be very difficult to replace.

Sensor-to-display conversions

In many instruments, the outputs of sensors are not in the best form for display to the user. For example, inputs to transistor curve tracers may be in the form of collector current or base-step information, but the user would like to see a display of the β of the device.

Often, this sensor-to-display conversion process can be performed by arithmetic operations handled by simple microprocessor routines, but in many other cases, the conversion—often referred to as a linearization—is nonlinear. For example, the nonlinear relationship between the millivolt output of standard thermocouple materials, and temperature in °C, is defined in widely used tables issued by the U.S. National Bureau of Standards. In actual fact, these tables are based on curves defined by polynomials.

With a microprocessor, it is feasible to use the polynomials themselves—their form and coefficients are available from NBS—to calculate the necessary conversion factors. The conversion tables can be built into instruments by storing them in semiconductor memory, but lists of polynomial coefficients are more compact, and the accuracy of the computed coefficients can be controlled by the instrument maker.

In an entirely different type of conversion, a microprocessor in the Hewlett-Packard 1722A Oscilloscope provides a digital readout of waveform dimensions. Here, the microprocessor is linked to the CRT display through a digital-to-analog converter that translates processor output numbers into the distance between two bright "markers" that appear on displayed waveforms. The operator positions these markers to line up with key waveform features (such as successive peaks in a repetitive waveform); and a digital light-emitting diode (LED) display shows the marker spacing as a time interval in microseconds or nanoseconds, etc.

In this instrument, the key set of operator controls actually increments a computer-stored number that determines the LED display and also—via the DAC—causes the marker on the CRT to move. A similar arrangement is used to make the LED-display numbers correspond to the average or instantaneous amplitude in volts, of incoming waveforms. Computed conversions allow direct readout of frequency values and of percent readings.

Some additional examples will indicate other types of sensor-to-display conversions currently being performed with the aid of microprocessors.

- In the Bell Laboratories cable-length test set, calculated readings are obtained in binary-coded decimal form. To display these readings, they need to be converted into signals for a seven-segment numerical display. This conversion process is carried out by a microprocessor subroutine.
- The Hewlett-Packard electronic distance meter uses its microprocessor to convert readings from feet to meters with the flip of a switch.
- In the Model 76A capacitance bridge (Boonton Electronics, Boonton, N.J.), measured capacitance and conductance are converted, via microprocessor programs, to display such parameters as dissipation, Q, equivalent series capacitance, and equivalent parallel resistance.
- In the Digitrend 220 data acquisition system, current signals from transducers are converted to millivolt signals by passing them through standard resistors; offset values are then subtracted out, by a simple microcomputer program, to give corrected readings.

Helping with test and maintenance

Instrument manufacturers seem uncertain about how important microprocessor-implemented diagnostic, troubleshooting, and checking capabilities will be, as a feature of their new instruments.

For some of the more complex instruments, the feeling seems to be that the user would not be capable, even with computer assistance, of maintaining his own instrument. Still, at instrument factories, many diagnostic programs are already in use to help with alignment and checkout of instruments, subassemblies, and components; and these programs could also be available for maintenance and report purposes.

Microprocessor-assisted diagnosis and testing can take a number of forms. These functions can be operated entirely from the instrument control panel through built-in equipment. In some cases, available memory space in ROM or PROM memories may accommodate small test programs as well as the routines that normally operate the instrument. Or, built-in memory can be added, specifically for test purposes. An alternative method is to use plug-in diagnostic cards that contain the test memory along with any needed test circuits.

Plug-in ROMs and PROMs can be helpful in adding diagnostic and test capabilities, and they can also make instrument field changes easier since new control programs can sometimes be tested without rewiring the instrument.

A few examples are available of built-in test and maintenance capabilities in existing microprocessor-based instruments.

- The H-P electronic distance measurement instrument includes a self-test feature. With this, the microprocessor runs the instrument through a series of internal tests to detect any malfunction. This feature is a boon to surveyors who like to know that their equipment is in working order before they drive hundreds of miles to a job in a remote area.
- The Digitrend 220 data acquisition system uses microprocessor instructions to order the display of flashing indications of such conditions as alarms, open transducer leads, power interruptions, and low print-paper supply.
- Diagnostic information can sometimes be generated as a by-product of microprocessor-based instrumentation. For example, in the Process Control Systems torque-reading system, crossed threads are indicated by a faster than normal buildup of torque. Thus, a fastener that reached rated torque in only 50 ms, when this should normally have taken 100–300 ms, would be suspect. Similarly stripped threads produce a slow torque build-up.

What makes a good interface?

Flexibility, reasonable cost, and compatibility are musts when interconnecting independently manufactured devices into a workable system

As marketplace pressures have mounted for more sophisticated and more widely applicable instrumentation systems, the instrument designer has turned to an increasing variety of programmable instruments—this, to the delight of the systems engineer seeking improved performance from system components. But the benefits that should be flowing from these efforts of the designer are not always being realized simply because the communication links that interconnect sets of system components have not been optimized.

It is the *complete* communication link—or "interface system"—that enables interconnected system components to communicate effectively. In general, this interface system involves much more than an interconnecting cable and first-level interface circuitry (drivers and receivers). It also involves designing around interface incompatibilities that can be costly to remove—reversal of the logic sense of a status bit, for example, or translation of an otherwise incompatible data code pattern, addition of a missing timing or control line, adjustment of incompatible voltage levels, or adding a buffer to accommodate high data rates, to mention just a few possibilities.

Overall objectives

To provide an effective communication link, an interface system must offer flexibility, reasonable cost, and compatibility. In addition, an interface system should permit the interconnection of independently manufactured instruments and system components, whether from one or several manufacturers, into a single functional system.

A flexible interface system will be capable of communicating with a wide spectrum of products, which are required if an instrumentation system is to solve real-world problems. Typical stimulus-response test systems must have both measurement and stimulus devices, in addition to some form of controller to program the system. If human interaction is needed, then a keyboard/display device is called for. Frequently, bulk storage of measurement results is desired for subsequent analysis, hence the need for a storage device. A versatile interface, therefore, must be compatible with at least five major categories of system components (see Fig. 1)—measurement and stimulus equipment, displays, storage units, and a means of control.

A general-purpose interface system must be compatible with a wide variety of processor elements—from a simple paper tape reader all the way to a minicomputer. Whatever the range of controllers, a given measurement instrument's interface should, if possible, remain unchanged for maximum versatility. In fact, very small system configurations require the ability to interconnect a measurement instrument and a digital recorder without a controller within the *same* interface scheme.

Another major objective is to define an interface that is cost-effective, both initially and during operation of both the small two-component system and the larger computer-controlled system. This implies minimizing not only the number of interface signal lines but other hardware such as cables and logic circuits as well. Thus, an interface can be partitioned in such a way as to make the interface circuitry incremental with the addition of each device to the system, thereby eliminating the need for entirely separate devices (e.g., couplers).

The third objective—compatibility—implies the ability to handle a wide range of data rates (asynchronous, if possible), data codes, and communication paths. Compatibility is further improved if the interface system can use a common, widely used code, such as ASCII (ISO 7-bit code), that is relatively easy to generate, display, and interpret. Further, an interface system must be capable of handling, without modification, variable message lengths and permitting connection of just the required number of system components (to an upper limit).

Interface system features

The characteristics of an interface system take on varying degrees of significance depending upon the

Donald C. Loughry
Hewlett-Packard Company

> **A proposed standard**
>
> The interface system described in this article is presently under consideration as an IEEE Standard and an IEC (International Electrotechnical Commission) Recommendation. Work has proceeded rapidly on the byte-serial system at both the national and international levels, and over 15 individuals from as many different companies have contributed to the evaluation and evolution of a draft document within the U.S. Similar representatives from six nations have participated actively over the past two years in the formulation and critiquing of several draft documents.
>
> Interest in the proposed interface system as a practical standard for programmable instrumentation has been significant and it is anticipated that the system will achieve widespread usage. It is you—the instrument and system designer and user—however, who will make the final determination as to whether or not this interface system justifies its use, thus reducing the birth pangs of modern-day instrumentation systems.

application to which the system is applied. The following key features are considered most significant for a variety of common applications; specifically, an interface system

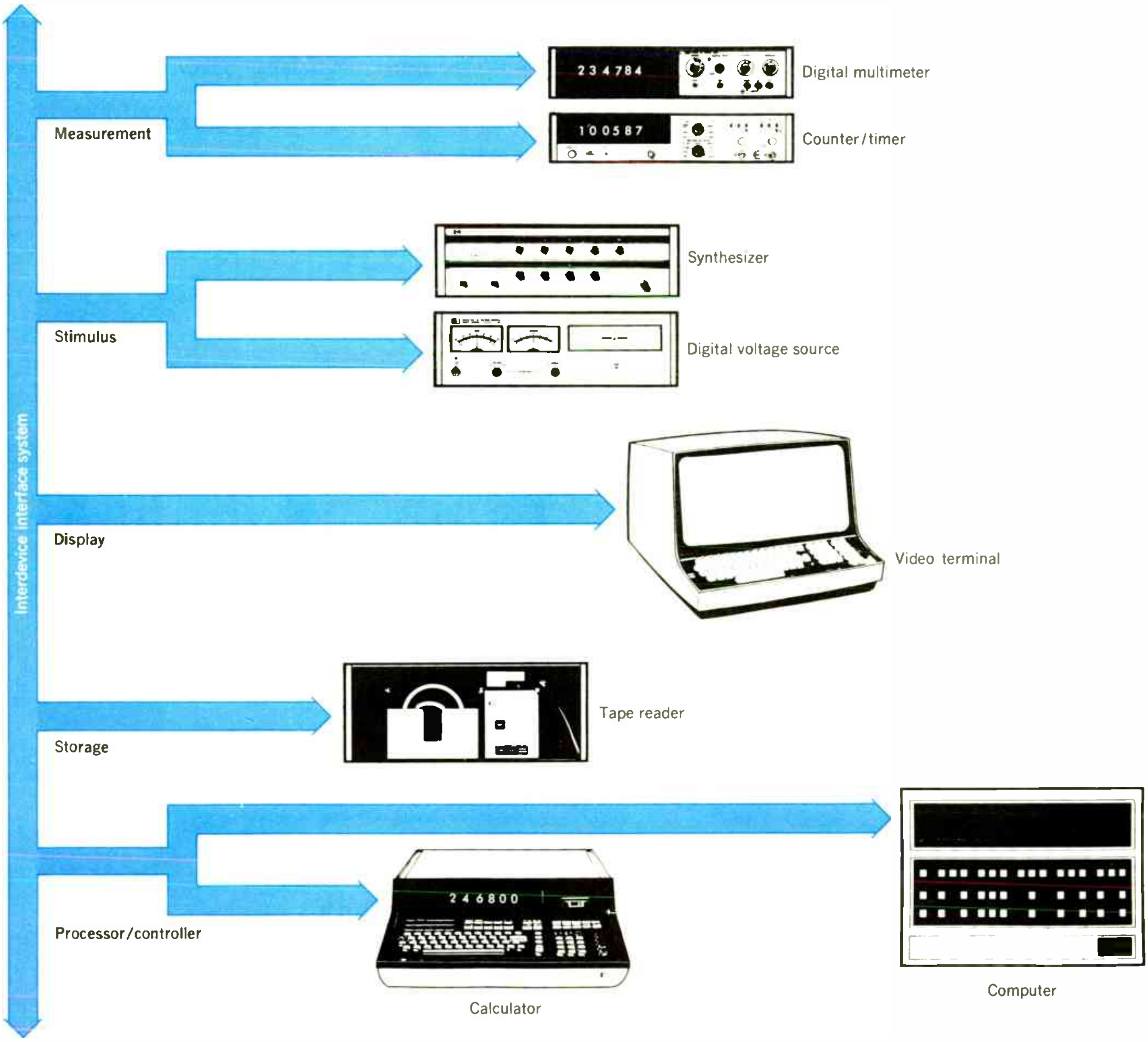
- Uses a simple interface structure
- Interconnects a wide variety of products
- Accommodates both simple and complex controllers
- Uses asynchronous communication
- Interconnects both high- and low-speed devices
- Allows data code, data rate, and data path changes
- Permits unrestricted data code use
- Transfers control among interconnected devices
- Enables direct data transfers
- Allows multiple listeners

The relatively simple interface structure provides a cost-effective solution for small as well as large products. Interface capability for a programmable counter on line as a talker, listener, and six other interface functions (see Box, pp. 56–57) costs less than $400 (not even 7 percent of the total cost of the instrument). On the other hand, the cost of a simple listen-only device may be under $400, total, including both the device and its interface capability.

Use of an asynchronous data transfer technique permits a mixture of high- and low-speed devices to communicate effectively without unnecessary timing restrictions. A controller, for example, can output data at high rates to a storage or display device during one message sequence and then output program data to another device at a much slower rate.

At times, it is useful to shift control (the capability to address other devices and send commands) from one system component to another. Though this capability is always delegated, never assumed, it adds significantly to the flexibility of the system performance.

[1] In general, an interface system must be compatible with instrumentation that provides both stimulus and measurement capability, display terminals, storage units, and a controller.



The transfer of data directly between affected devices reduces the message traffic volume. A voltmeter, for example, can output a single measurement result concurrently to a digital recorder, graphic display, and controller for further data reduction.

A feasible interface standard

The overall purpose of an interface system is to provide an efficient method of communicating messages among interconnected system components in an orderly and unambiguous manner. The following are major considerations required in defining and using such a system.

Practical limitations: No single interface system is the panacea for all instrumentation system requirements—real-world needs are much too diverse! Similarly, one interface system is unlikely to fulfill an unlimited number of applications.

Four basic questions common to an instrumentation system communication link focus on the most frequently encountered requirements for an interface system:

- What number of devices need to communicate?
- What distances are involved?
- What messages need to be carried?
- What data rates are required?

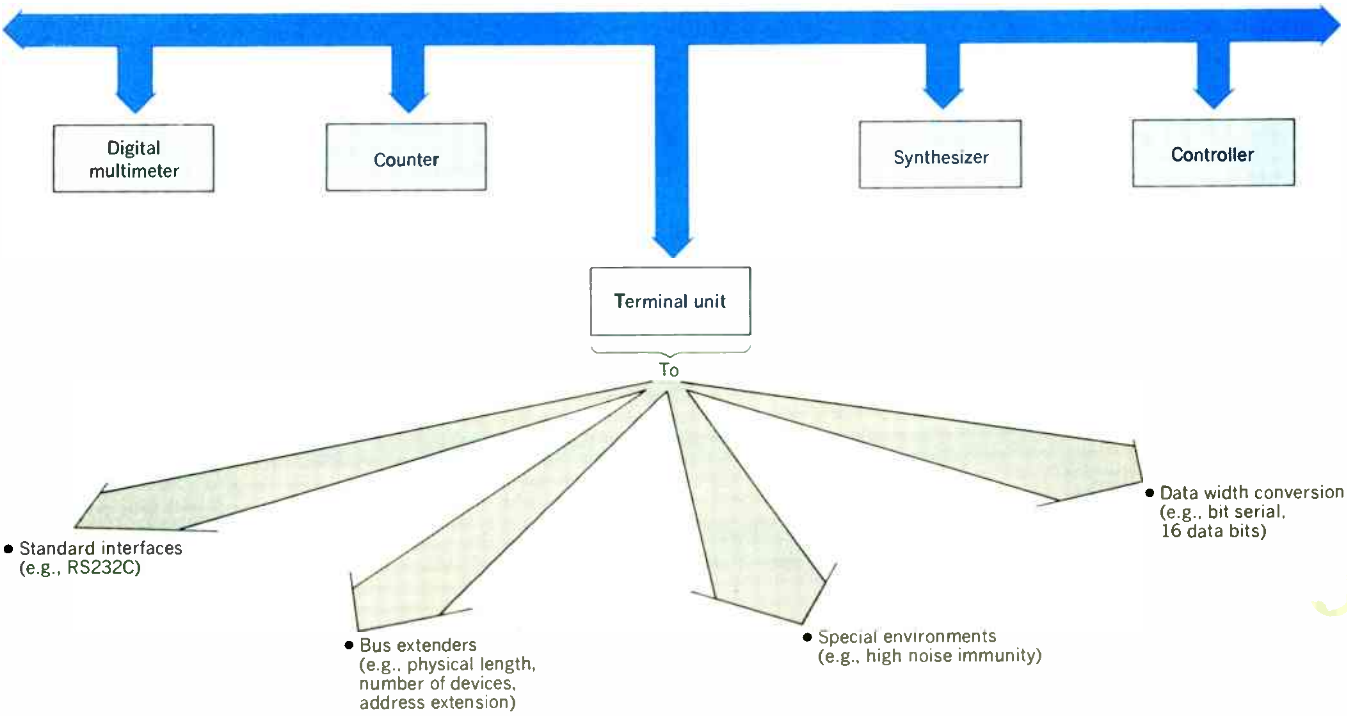
In considering the quantity of devices, transmission path length, message characteristics, and data rates, it is assumed the interface is a digital one (as distinct from an analog interface) to program instruments and retrieve the measured results. First, the total number of instruments, controllers, and associated devices in the average system is usually between 10 and 20. More devices may exist in some large systems; however, not all devices are required to communicate with all other devices. Therefore, an interface system with the capacity of communicating directly among 15 devices over one contiguous bus satisfies the majority of needs. Systems requiring larger numbers of devices may be organized into task-organized sets of devices, each connected to physically separate but functionally related buses.

Second, the majority of instruments and devices are usually located close to one another, in adjacent cabinets. A total transmission path of 20 meters is adequate for most cases. If a bus structure is used wherein physical interconnection may be made using either star or linear bus networks, as required, then need for longer transmission paths diminishes and the feasibility of the interface structure increases. For certain applications, much longer distances are required between system components. Figure 2 illustrates the use of a terminal unit to accommodate these special requirements. This approach increases the feasibility of the interface system by not burdening every system component with the need to adapt to special interface needs.

Third, evaluation of the preponderance of messages in instrumentation systems reveals a relatively short message length. A digital multimeter may require 10–12 bytes of data to be programmed completely; the measurement results, however, are contained within 10–20 bytes of data:

DMM program data	DMM output data
FØR4TØM3E	OLDC+120002E-4
(i.e., a single 10-volt dc full-scale reading triggered by an internal clock)	(i.e., +12.0002 Vdc)

[2] **Although the majority of interconnected instruments are usually within a 20-meter transmission path, some system components demand longer distances; then, special terminals must be used.**



Hence, the interface structure needs to be capable of efficiently handling short, intermittent messages to and from many instruments and devices throughout the system.

Fourth, the majority of instruments are neither programmed nor output at data rates in excess of tens or hundreds of kilobytes per second, though the trend is certainly toward faster rates. Instruments such as analog-to-digital converters and data peripherals such as magnetic-tape transports operate at much higher rates, some of which are far above the norm. A maximum asynchronous data rate of 1 megabyte/s appears to provide a reasonable compromise between speed, cost, compatibility, and flexibility.

Interface characteristics: A complete interface system includes four primary sets of characteristics—mechanical, electrical, functional, and operational. The mechanical nature of connectors and cables are obvious and basic to an interface; this may also be the easiest and least costly portion of an interface to implement. However, without this "first level" of compatibility, the rest of the interface may be of small value.

Electrical characteristics define the driver and receiver circuit parameters and require full compatibility—Ohm's law has a sharp eye for violators. The functional nature of an interface system includes the complete repertoire and precise definition of each of the signal lines, the exact protocol and timing relationships used to transfer all messages across the interface, and the responses expected as a result of receiving certain of these messages.

And as for making the system operational, there are those characteristics that tend to be highly dependent on and unique to the specific device or instrumentation system to which the interface system is applied. (The specific device-dependent codes used to program a DMM are operational in nature. The operating system and application software of a complete system are operational in nature.) Although the distinction between all of the functional and operational characteristics is not always precise, the latter tends to be sufficiently device- and system-dependent to the point of jeopardizing the feasibility of a widely useful interface standard.

To sum up, mechanical, electrical, and functional characteristics enable a common industry interface system to be widely useful to the extent that their definition and application remains device and instrumentation-system independent. In turn, interface standard feasibility depends, to a large extent, on these device-independent and system-independent characteristics!

Compatible implementation: One goal of a standard is to provide the basis for broad compatibility among products, each of which is designed by different engineers at different times and places and for different applications. Achievement of this goal certainly requires consideration of the standard's content. Just as important, however, is the organization, structure, and method of presentation of the technical content.

Low cost and compatibility among a wide range of products presents a contradiction in that low cost suggests minimal interface capability and circuitry, whereas a wide spectrum of product compatibility suggests comprehensive interface capability and circuitry. The feasibility of an interface system is increased significantly if the designer is given the opportunity to select just those portions of the interface required for a particular product. The proposed interface system contains two basic degrees of freedom open to the design engineer within the functional characteristics of the interface system—a choice of interface functions and a choice of allowable subsets within each interface function. Cost and capability are then balanced to fit a particular need. Both the interface functions and the method for describing them are outlined in the box on pp. 56–57.

Instant system syndrome: It is human nature to anticipate the supposed ease with which a "standard interface" will eliminate all annoying and costly interface problems. After all, isn't that what a standard is for? The line is a fine one between eliminating all interface problems and satisfying a limited set of instrumentation problems or, conversely, solving a large portion (not all) of interface problems and satisfying a much more extensive set of instrumentation problems—all within reasonable resource constraints and limitations.

The common household light bulb is a good case in point. A "standard" screw-in-type lamp has a common mechanical thread size, voltage rating, and possibly a fixed functional coating for light diffusion. Beyond these "standard" characteristics, the variety of functional choices is immense. Wattages vary to satisfy different light intensity needs and some lamps contain two or three elements to provide adjustable light levels. Then there are the countless varieties of color, size, and shape—each to satisfy a specific functional application requirement. Would you be satisfied with light bulbs in your home all having identical color, size, shape, and wattage ratings?

An interface system with the stated objectives is no different when it comes to feasible implementation. The mechanical and electrical specification can indeed be standard. Most functional specifications can also be used in common by many instrument designers since they tend to fall into the device- and system-independent category.

The operational characteristics of instruments and systems depend very much on specific goals or applications. It is helpful to ask the designer of an instrument to distinguish between device-independent and device-dependent performance characteristics. Integrating together the device-dependent characteristics of several instruments into an instrumentation system to perform a specific application requires additional engineering beyond what is feasible to include within the framework of a standard interface system.

A feasible interface standard does not provide instant systems unconditionally. It is the responsibility of both parties, the designer and the user of programmable instruments and systems, to create an operational system. The designer must define precisely all of the device-dependent characteristics of the instrument within reach of the interface system. Moreover, the system designer, or user, must not only understand the end application but must also examine both the extent to which the functional capabilities have been implemented within each instrument as well as the unique device-dependent features. Full operation-

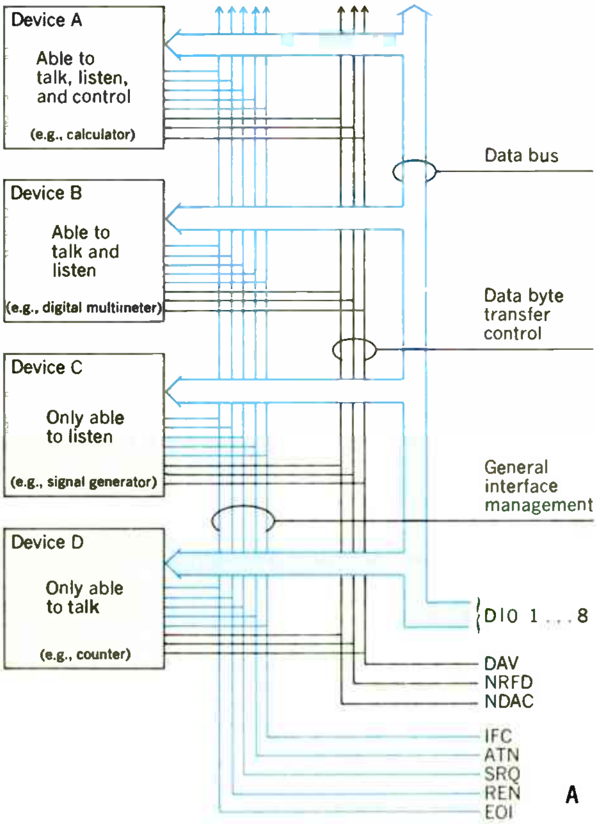
Interface system concepts

An interface system is, by its very nature, only a means to an end—the performance of a series of measurements on a device under test or the monitoring of some continuous process and the application of some appropriate control. A measurement or monitoring function requires that unique messages, which are a function of the unit under test or process being monitored, be carried among the interconnected devices to and from a central control point. It is these *device-dependent messages* (e.g., program data, measurement data, status data) that the interface system must carry in an organized and effective manner.

In addition, an interface system must carry another group of messages called *interface messages*, which do not interact directly with the measurement process, but interact only with the interface logic within connected devices. The primary purpose of these messages is to carry out the proper protocol in setting up, maintaining, and terminating an orderly flow of device-dependent messages. For example, address data designating either the origin or terminal point for subsequent device-dependent messages is an obvious interface message candidate. Commands that are universal in nature (commands to which all devices must respond) such as "Interface Clear" and "Device Clear" are another group of interface messages. A third group, called *addressed commands*, consists of a combination of the first two groups; "Selected Device Clear" and "Group Execute Trigger" are examples of addressed commands. Only devices addressed to receive them will respond.

Basic elements

An effective communication link requires three basic functional elements to organize and manage the flow of information among devices: a device acting as a *listener*, a device acting as a *talker*, and a device acting as a *controller*. These functional elements are shown in Fig. A as they



A

might be found among typical instrument system components.

A device with the capability to listen can be addressed by an interface message (originating in a controller) to receive device-dependent messages from another device. A device with the capability to talk can be addressed by an interface message to send device-dependent messages to another device. A device with the capability to control can address other devices to listen or talk and, in addition, can send interface messages to command specified actions within other devices. It is to be emphasized that these are capabilities related to the interface system and may be combined when required to carry the necessary device-dependent messages.

The interface system of Fig. A contains a set of 16 signal lines used to carry all messages, both device-dependent and interface messages, among interconnected devices. The bus structure is organized into three sets of signal lines.

Eight "data input–output" signal lines (DI01 through DI08) carry all 7-bit coded interface messages and all device-dependent messages (1 to 8 bits). The messages on these signal lines are carried in bit-parallel byte-serial form. Information flow is bidirectional in that an individual device can use the 8-bit bus to either input or output messages. Due to the nature of the data byte transfer process, information flow on the DIO lines is asynchronous at the rate of the slowest device communicating over the interface at a given time. This process not only accommodates a wide range of devices but permits high-speed communication among addressed devices while other slow-speed devices connected to the bus are not addressed to talk or listen.

A set of three interface signal lines is used to effect the transfer of each byte on the DIO signal lines from an addressed talker to all addressed listeners. The "data valid" (DAV) signal line is used to indicate the condition (availability and validity) of information on the DIO signal line. The "not ready for data" (NRFD) signal is used to indicate the condition of acceptance of data by a device(s). The DAV, NRFD, and NDAC ("no data acquired") signal lines operate in what is called a three-wire (interlocked) handshake process to transfer each data byte across the interface.

Five interface signal lines are used to manage an orderly flow of information across the interface: "attention" (ATN) is used to specify how data on the DIO signal lines are to be interpreted and which devices must respond to the data; "interface clear" (IFC) is used to place the interface system, portions of which are contained in all interconnected devices, in a known quiescent state; "service request" (SRQ) is used by a device to indicate the need for attention and to request an interruption of the current sequence of events; "remote enable" (REN) is used (in conjunction with other messages) to select between two alternate sources of device programming data; "end or identify" (EOI) is used to indicate either the end of a multiple byte transfer sequence or, in conjunction with an ATN, to execute a special polling sequence.

Interface functions

To accommodate the large spectrum of device capabilities encountered in instrumentation systems, it is necessary to partition the overall interface system functionally and in an effective way. Given appropriate alternatives, the design engineer is free to select the *interface functions* required for each particular design, thus increasing the feasibility of a useful and practical standard.

The interface system contains ten interface functions from which the design engineer can choose. These interface functions provide the basic capabilities of the talker (T), listener (L), and controller (C), as well as the source (SH) and acceptor (AH) handshake functions, to transf[er] each byte of data across the interface. In addition, th[e] auxiliary interface functions of service request (SR), remote local (RL), parallel poll (PP), device clear (DC), and device trigger (DT) are defined to serve special needs. In turn, these interface functions interact with the *device functions* to form a complete operational unit. The interface system specifies the total spectrum of interface functions the designer may choose from; however, the designer is free to implement whatever device functions are essential to the particular application at hand.

State diagrams

Interface system compatibility of independently designed and manufactured devices depends, to a large extent, on the thoroughness, accuracy, and lack of ambiguity with which the interface functions are defined. Each interface function is therefore defined in terms of a state diagram to prevent, if at all possible, misinterpretation of the interface protocol and functional specifications.

Electrical and mechanical specifications

The electrical interface is defined in terms of standard TTL logic voltage levels and current limits. Open-collector drivers and Schmitt receivers are specified for normal use with tristate drivers available for high-speed applications. Each signal line is terminated with a resistive divider load that is considerably higher than the characteristic impedance of the interconnecting cable. In this way, the load is distributed among all devices and only passive cables need be used to interconnect a system physically.

The proposed mechanical interconnection scheme uses a piggyback connector assembly to conserve panel space, minimize the total requirement for cables, and permit either a star or linear bus cabling network as dictated by the physical racking of equipment.

A summary of interface system specifications is given in the table.

Interface specifications

Interconnected devices:	Up to 15 maximum on one contiguous bus.
Interconnection path:	Star or linear bus network over 20 meters total transmission path length.
Signal lines:	Sixteen total; eight data lines and eight lines for critical control and status messages.
Message transfer scheme:	Byte-serial bit-parallel asynchronous data transfer using interlocked three-wire handshake technique.
Data rate:	One megabyte per second maximum over limited distances; 250–500 kilobytes per second typical over full transmission path.
Interface function:	Ten total; five primary communication functions and five special-purpose functions.
Address capability:	Primary addresses, 31 talk and 31 listen; secondary (2-byte) addresses, 961 talk and 961 listen.
Control shift:	May be delegated, never assumed, with a maximum of 1 talker (up to 14 listeners) at a time.
Interface circuits:	Driver and receiver circuits TTL-compatible.

al use of the interface system is not achieved until both parties have carried out their responsibilities fully.

Technology assists: It would be a serious omission to ignore the role technology is playing in support of a feasible standard. The widespread availability of SSI and MSI integrated circuits has enabled the implementation of cost-effective logic circuitry within the functional portion of the interface. Cost-effective data storage—essential in programmable instruments connected to a party-line bus structure would be difficult without today's components. Again, with the aid of technology, intelligent instruments have become a reality. The smart instrument tends to reduce the message traffic volume over the interface and therefore provides greater flexibility and freedom in the instrument system design as well as increased instrument capability.

Although many have contributed to the evolution of this interface system, I particularly thank Daryl E. Knoblock, Gerry E. Nelson, and David W. Ricci for their outstanding contributions to the overall concepts, and to H. H. Freytag, Manfred Richter, Chris Vissers, and Marion Perron for their significant efforts.

BIBLIOGRAPHY

Bond, J., "Computer-controlled instruments challenge designers' ingenuity," *EDN*, vol. 19, Mar. 5, 1974.

Fisher, P. D., and Welch, S. M., "Part two: how to build an automated system around a programmable calculator," *Electronics*, vol. 47, May 16, 1974.

Fluke, J. M., Jr., "What makes an instrument truly system compatible?" *EE/Systems Engineering Today*, vol. 32, May 1973.

Levine, S. T., "Instrument interfacing can be done—but it takes a bit of doing," *Electronic Design*, vol. 24, Nov. 22, 1973.

Loughry, D. C., "Digital bus simplifies instrument system communication," *EDN*, vol. 17, Sept. 1972.

Loughry, D. C., "A common digital interface for programmable instruments: the evolution of a system," *Hewlett-Packard Journal*, vol. 24, Oct. 1972.

Loughry, D. C., "Instrument communications: a new interface system," presented at IEEE INTERCON 73.

Nelson, G. E., and Ricci, D. W., "A practical interface system for electronic instruments," *Hewlett-Packard Journal*, vol. 24, Oct. 1972.

Socolovsky, A., "The happy state of a standard," *EE/Systems Engineering Today*, vol. 32, May 1973.

More to come!

This is the first of a two-part article, the second of which—to appear sometime early next year—will deal with the technical details of the proposed interface system described on these pages.—*Ed.*

Donald C. Loughry (M) started out at Hewlett-Packard in 1956 as a production test department manager and, in 1958, moved to the development laboratory to work on custom and standard systems. In 1963, he became engineering manager of the Dymec Division. He has been in his present position of corporate interface engineer since 1968, and in that capacity is responsible for companywide interface guidelines and services. Mr. Loughry is a graduate of Union College, where he received the B.S.E.E. degree in 1952, and when he's not busy interfacing, his interests range from gardening and photography to camping and star-gazing (he grinds his own telescope lenses). He is active in various groups working on interface standards, including IEC, ISO, and ANSI.

Have instrument, will travel

Be the readout analog, digital, CRT, or hard copy, "portable" and "performance" are now in the same package

Once upon a time, remote troubleshooting consisted of curiosity, courage, and the judicious application of two moistened fingertips. But field engineers, servicemen, and others who must work "on location"—as opposed to the controlled environment of a well-stocked lab—have constantly demanded rugged, manageable, and accurate test equipment. To this need, the integrated circuit, coupled with digital readouts and improved battery packs, has brought a welcome revolution. Oscilloscopes, function generators, strip chart recorders, spectrum analyzers, as well as vastly improved volt-ohm milliammeters, are now ready to go wherever the problems are. And variety doesn't stop with these familiar items. New types of instruments such as a portable digital thermometer, which measures surface temperatures *without* physical contact, have helped turn difficult and costly analysis into routine field checks. In fact, the best perspective on current progress and future trends is gained from a good look at some currently successful and recently announced portable instruments.

New face for an old friend

Perhaps the piece of portable instrumentation most familiar to any engineer is the volt-ohm milliammeter (VOM). Consisting of a high-impact molded case enclosing simple but dependable electronics, a couple of inexpensive batteries, and a large multiscale meter, the general-purpose VOM is probably best characterized by the Simpson Electric Co.'s model 260. For 37 years, the 260, with its complement of test leads and probes, has maintained a popularity and continuity of external appearance rivaled only by Volkswagen.

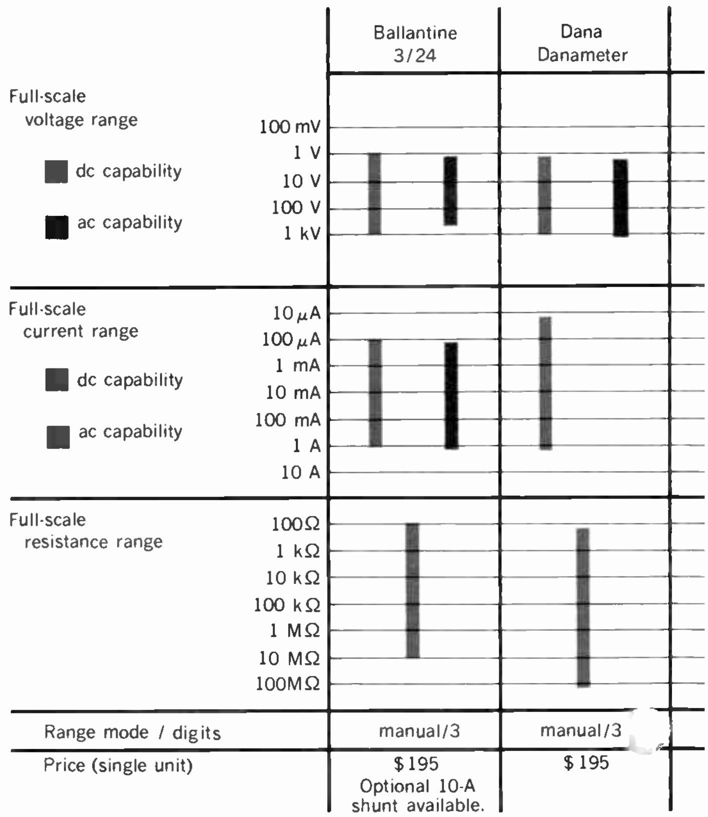
But the introduction of low-cost digital displays over the past several years has changed the face of much portable test equipment. While Simpson continues to sell more 260s than ever (at the current price of $74.50), the interpretive-free convenience of digital readouts has been recognized. Providing a choice of ac line or NiCad battery operation, Simpson's model 360 VOM (at $295) features an LED display *plus* a small analog indicator for scanning peak and null measurements.

Customers preferring a lab-style metal case and an extra-large digital readout are offered Simpson's model 460 VOM (at $395), which includes automatic blanking of nonsignificant zeros and extended battery life—up to nine hours on a full charge.

Meanwhile, many other new, interesting, and competitive multimeters are being offered to the engineering community in both digital and analog varieties. Dana Laboratories, Inc., Irvine, Calif., for example, has introduced their Danameter with liquid crystal digits as a direct challenge to established analog VOMs. Some key features include automatic polarity, for dc voltage measurements, a tough case of molded cycolac, and one year's normal use on a single 9-volt battery. The price: $195 complete.

On the market about a year now is the 970A, a hand-held digital probe from Hewlett-Packard, Palo Alto, Calif. Battery-powered, pocket-sized, and completely self-contained, the 970A's controls consist of two thumb-actuated slidebars and a push-to-test lever for measuring ac volts, dc volts, and ohms. Circuit connections are made through a ground clip and a movable–removable probe tip. A standard banana plug with a clip lead can mount in the probe socket for measurements requiring two clip leads. A single MOS integrated circuit handles all the auto ranging and polarity adjustments, settling to yield a proper reading in less than two seconds (typical). The 200-gram 970A sells for $310 and will make over 2000 measurements on a full charge of its NiCad battery.

Predating the HP 970A by at least a year is the model 167 auto-probe digital multimeter from Keith-



Don Mennie Associate Editor

ley Instruments Inc., Cleveland, Ohio. Physically unique among portable multimeters, the 167 features a probe-mounted display linked to the function selector and probe cradle via a special cable. Auto ranging and autopolarity, plus push-to-test operation, conserve the batteries while speeding multipoint measurements. And the 167 converts to a typical "bench" configuration simply by inserting the probe into the cradle and then connecting standard test leads to the front-panel banana jacks (the probe's LED numerics continue to serve as the readout). Probe, case/cradle, and alkaline battery set come complete for $375.

While HP and Keithley have settled on LEDs as the standard readout for portable gear, Data Precision, Wakefield, Mass., offers a high-intensity plasma display on model 245, a $295 miniature digital multimeter. The rechargeable batteries last about six hours and a high-impact case protects the instrument from everything but overzealous borrowing. Range switching is manual, but LSI and CMOS circuitry handle autopolarity and automatic zeroing.

Apparently successful with the 245 since its introduction two years ago, Data Precision has now gone after the lab instrument market with the basic performance features of the 245 packaged for benchtop use. Introduced in August at $325, model 1450 is a 4½-digit ac-powered multimeter that, like the 245, derives its accuracy from a carefully maintained +1-volt zener reference.

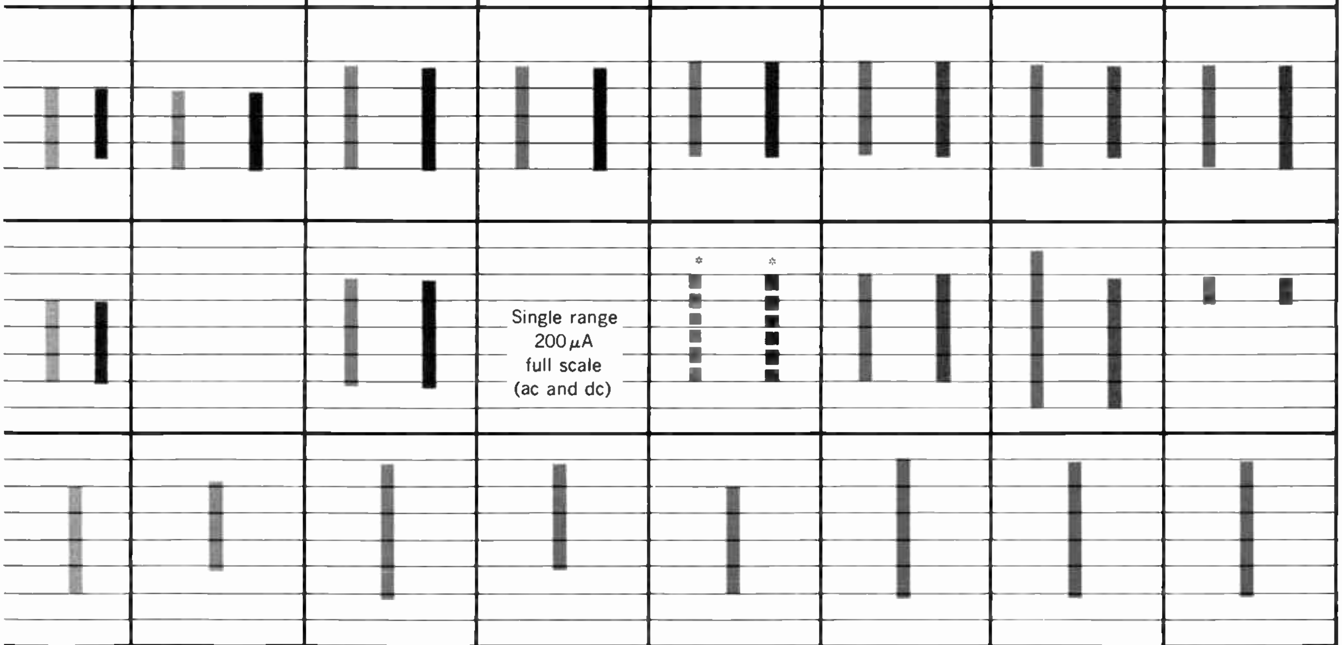
Contoured like a calculator and operating off rechargeable NiCad batteries, Data Technology's model 21 offers ac and dc volts, resistance, and capacitance measuring capability combined in a hand-held multimeter. Users have the choice of continuous operation or extending battery life with a push-to-read button. For an extra $10, a push-to-read probe allows hands-free testing while conserving battery power. An impact-resistant polycarbonate case, handy carrying pouch that clips on your belt, and 0.68-cm LED readouts help the $269 model 21 perform under rough field conditions.

But as the popularity of Simpson's 260 will testify, analog multimeters have not fallen categorically to the digital onslaught. Weston Instruments, Inc., Newark, N.J., for example, has recently introduced model 670, an analog VOM which can measure direct current on printed circuit boards *without* breaking connections. This ac powered "in-circuit" tester uses two special dual-tip probes for measuring direct current. Best results are obtained by probing the longest or narrowest continuous conductor available. One contact in each probe senses the voltage drop on the current-carrying conductor under test. A differential amplifier senses this condition and generates a bucking current until it balances the voltage drop. This bucking current is proportional to the circuit current and is read on the meter. Housed in a shock-resistant polycarbonate thermoplastic case, the 670 lists for $249—including

Even a modest budget of around $300 allows wide selection from among the many compact, battery-powered digital multimeters currently available. Still don't see the performance you need? Remember, most of the manufacturers listed produce a wide variety of digital instruments. Perhaps the hardest parameter to compare among competing DMMs is accuracy. Usually it is given as a percentage of reading ± one least significant digit, or ± a percentage of full-scale range. Zero stability, temperature coefficients, and frequency sensitivity can be cited separately.

Make and Model number

Data Precision 245	Data Technology 21	Fluke 8000A	Heath SM-4440	Hewlett-Packard 970A	Keithley 168	Simpson 360	Weston 4442



m[illegible]/4½	manual/3½	manual/3½	manual/3½	auto/3½	auto/3½	manual/3½	manual/3½
$ 295	$ 269 (also measures capacitance)	$ 299	$ 250 (assembled)	$ 310 *Optional shunt available.	$ 299	$ 295	$ 295

Digital multimeters have undergone considerable "human engineering" on their way to the market. Hewlett-Packard's 970A (A) and Data Precision's 245 (B) emphasize the hand-held concept, while Fluke's 8000A sports a larger "push-buttoned" profile coupled with a multiposition support handle (C). Meanwhile, Keithley's 167 combines a unique probe/readout with bench-mounted electronics (D).

standard test leads and the two-terminal current probe set.

Looking without lugging

While compact multimeters have long been associated with every collection of portable electronic service gear, overall bulk and power requirements have kept oscilloscopes stranded on the workbench until relatively recently. True, battery-operated scopes have been on the market for some time—Tektronix' model 321 featuring battery power was introduced in 1960—but the obvious ground loop isolation these instruments provided was certainly an advantage that equaled any portability they afforded.

Not so with equipment developed over the past three years by Tektronix Inc., Beaverton, Oreg., Philips Test & Measuring Instruments Inc., Woodbury, N.Y., and Vu-Data Corp., San Diego, Calif. Termed "miniscopes" by their manufacturers, this new test equipment offers compactness and weight advantages that make it ideal for on-site maintenance.

"Miniscopes," such as this Tektronix model 221, are partricularly helpful for servicing digital equipment.

Tektronix produces four such instruments in its 200 series of portable scopes including the single trace 211, dual trace 212, and the 214, a storage version of the 212. The latest from Tek, model 221, introduced this past January, features 5-MHz bandwidth, 5-mV/division vertical sensitivity, and 0.1-μs/division sweep speed packaged in an impact-resistant 7.6- by 13.2- by 22.9-cm case. An integral 1-MΩ probe shunted by approximately 29 pF minimizes circuit loading and is always there when you need it. Total weight for the 221 or any of Tek's other miniscopes is a scant 1.6 kg—including batteries! Prices range from $695 to $1075 for scopes in the 200 series.

Also offering 5-MHz bandwidth in a lightweight portable unit are Philips' PM3000/PM3010 models, which tip the scales at 1.8 kg each. The single trace PM3000 has a 10-mV/division vertical sensitivity and 0.3-μs/division sweep speed while the dual trace PM3010 offers 30-mV/division vertical sensitivity coupled with 1-μs/division sweep speed. Periods of battery operation may be easily extended from about five hours per pack simply by exchanging spent cells for fresh ones. Philips miniscope batteries are recharged independent of scope operation with the PM9398 ac power supply/battery charger that is included as a standard accessory. Measuring 8 by 12.5 by 19.6 cm, the PM3000 sells for $645 while the similarly packaged PM3010 is available for $775.

A slightly larger miniscope, Vu-Data's model PS910, delivers 20-MHz bandwidth, 10-mV/division vertical sensitivity, and 1-μs/division sweep speed in a 3.2-kg package, batteries included. Vertical and external trigger inputs are 1 MΩ shunted by approximately 47 pF. The 4.5- by 21.6- by 30.5-cm PS910 is a single-trace instrument selling for $645 (batteries extra).

Recently the PS910 has been joined by a somewhat larger dual-trace scope, the model PS940A, with identical bandwidth, vertical sensitivity, and input impedance. The fastest sweep speed on the PS940A, however, is 100 ns/division, and this miniscope includes a built-in delay line that allows the leading edge of a signal to be displayed. Self-contained lead-acid batteries bring the PS940A's total weight to 5.9 kg, while external dimensions are approximately 8.9 by 21.6 by 30.5 cm. Exclusive of batteries, extender cards, or other options, the PS940A sells for $1095.

While there are plenty of other battery-operated scopes available besides those just mentioned, the majority are considerably larger and heavier. They're "portable," but they won't follow you up ladders or into dark corners. Compact ac-powered instruments might be a better choice for field applications where line current is readily available.

Frequency vs. time

Performance is another factor that can affect your choice of portable equipment. Where electronic visual aids are concerned, field engineers may now select either a spectrum analyzer or a high-performance oscilloscope—without giving up battery operation!

This is an important option, especially to those concerned with analyzing complex sounds, mechanical vibrations, or communications signals. Sinusoids with only a few-percent distortion, for example, are not easily identified with a scope. But by examining this same signal in the frequency domain, even the faintest harmonics can be accounted for.

Introduced last year, Hewlett-Packard's model 3580A spectrum analyzer makes an excellent tool for sifting out the components of complex low-frequency signals. Tuning through a 5- to 50-Hz range with selectable bandwidths as narrow as 1 Hz, the 3580A can take over half an hour to make one full sweep across its CRT. This slow speed allows for the response time needed by the instrument's narrowband filters to give good separation of spectral components. But the frustration of watching a tiny dot drift across the display has been offset by digital storage.

While the sweep tunes at a rate compatible with the selected bandwidth, the resulting spectrum is stored in a digital memory. This memory is read and displayed completely every 20 ms, providing a flickerless image on a conventional CRT. Since updating the memory is still time consuming, an adaptive sweep feature allows "grass" to be ignored during successive passes—much like a standard baseline clipper. As a result, the sweep traces out significant harmonics only, bypassing the underbrush.

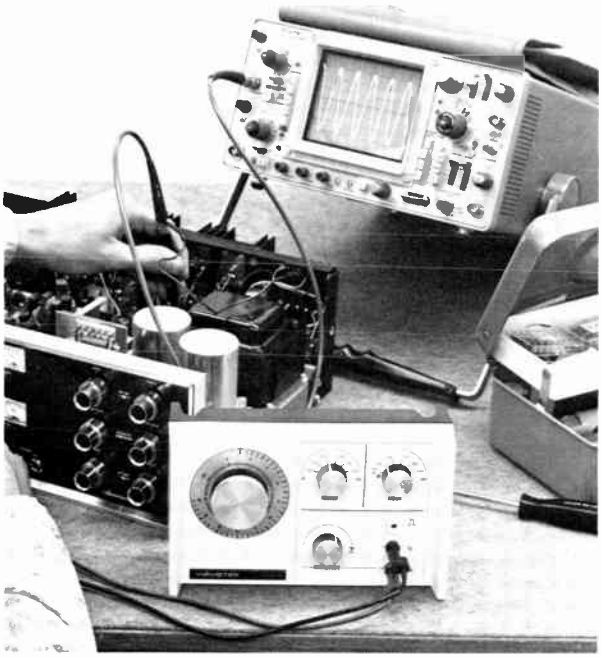
Other important 3580A parameters include an input impedance of 1 MΩ shunted by 30 pF, a weight of 15.9 kg, and a $4575 price tag. (These last two figures both include an optional battery pack.)

Short-order waves

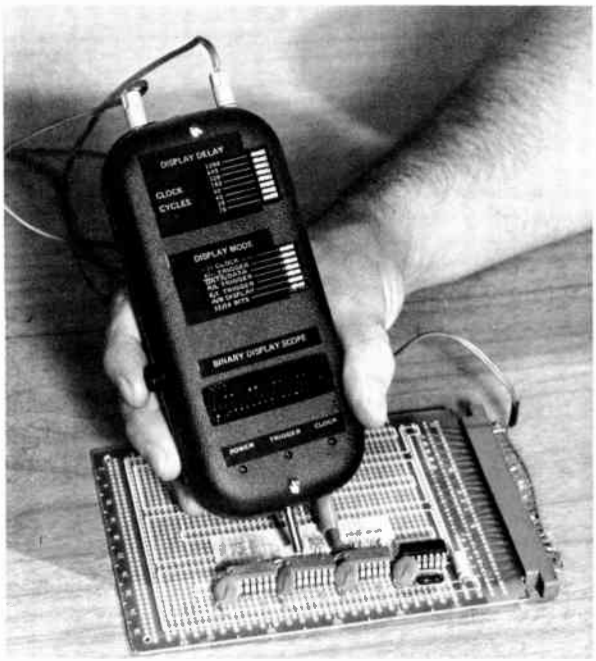
Besides tracking down and measuring elusive voltages and waveshapes, remote troubleshooting can also mean stimulating your ailing equipment by injecting a signal of known proportions. Several compact function generators are currently available for just this purpose, delivery custom-made sinusoids, ramps,

Vibration from heavy industrial equipment may be examined for telltale harmonics with Hewlett-Packard's model 3580A low-frequency spectrum analyzer.

Operating off a 9-volt transistor radio battery, Wavetek's model 30 function generator provides a 10-kHz sinusoid for checking out an ailing quadraphonic amplifier.



Destructive heat may hide among printed circuit board components, but it can't elude the William Wahl Corp.'s "Heat Spy," a digital infrared thermometer.



Capable of handling data rates up to 20 MHz, the model 0617B logic analyzer from CPSR, Inc., displays binary information on dual 16-bit rows of LEDs.

Portable strip chart recorders work on location while preserving data for later comparison and analysis. This Hewlett-Packard model 7155A has 0.1-mV to 10-volt per division input sensitivity, and disposable pens, which eliminate ink loading problems. Price for the basic unit is $985.

and square waves wherever they are needed.

The latest and lowest cost of several portable function generators made by Wavetek, San Diego, Calif., is the model 30, which can run up to eight hours off a conventional 9-volt transistor radio battery. Three frequency ranges provide sine, square, and triangle outputs from 2 Hz to 200 kHz. Open circuit output levels are approximately 1 volt rms for the sinusoid, 1 volt peak to peak for the triangle wave, and 50-percent duty cycle at nominal TTL levels for the square wave (0 to 0.5 volt low, 3 to 4.5 volts high). Weighing less than a kilogram, the model 30 retails for $149.95. The only option, a NiCad battery with recharger/power supply, costs an additional $25.

Bearing the same price, weight, and electrical specifications as the Wavetek model 30 is the fully portable model 195 function generator from Exact Electronics, Hillsboro, Oreg. The main differences between the two units are package layout and the location of various output jacks. All the waveforms generated by the 195 are available off the front panel, while some rear-panel outputs are employed on the model 30.

For about double the money of a 195 with options, Exact will sell you their battery-powered model 191. Generating sine, square, triangle, pulse, and ramp waveforms from 0.1 Hz to 1 MHz, model 191 delivers 20 volts peak to peak open circuit (10 volts into 600 ohms.) Sine wave distortion is typically 0.5 percent (versus about 2 percent for the 195 or the Wavetek model 30). Total price including battery pack and charger is $350.

Another versatile portable function generator is the model 5600 from Krohn-Hite, Cambridge, Mass. Both balanced 600-ohm and single-ended 50-ohm outputs are available for tapping the instrument's sine, square, and triangle waves. A single-turn, calibrated dial and four-position multiplier provide four bands covering 0.002 Hz to 2 MHz. Sine wave distortion is under 0.5 percent through 100 kHz, and no more than 3 percent to 2 MHz. Model 5600 is priced at $395 plus $70 for the battery kit. The complete unit weighs about 3.2 kg.

Hewlett-Packard also offers test oscillators (with a battery power option) in this approximate price, size, and frequency range. Models 209A and 204C operate from 4 Hz to 2 MHz and from 5 Hz to 1.2 MHz, respectively. They deliver sine and square wave outputs that can be synchronized with an external source. A battery- or ac-powered test oscillator, model 208A, is also available from HP with sine wave output only. Operating frequencies are 5 Hz to 560 kHz in five ranges with distortion less than 1 percent in all cases. The price: $613.

Hot, hidden, distant, or digital

Not every remote servicing need may be satisfied with standard electronic test gear. Sometimes special equipment provides the only practical solution. One such example is temperature measurement.

Two new solid-state thermometers featuring digital readout of temperature have been introduced by the William Wahl Corp., Los Angeles, Calif., in recent months. Model DHS-8E, an infrared thermometer known as the "Heat Spy," uses a light-beam sighting system especially suited to small areas such as electronic circuits. The hand-held Heat Spy requires no physical contact with its target, and delivers a stable reading in approximately one second. Accuracy is 0.5

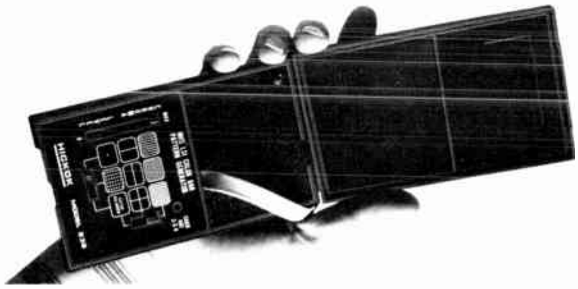
Mobile transmitters, restricted to precise frequency assignments, can be quickly field-tested with Hewlett-Packard's 5300 series measurement system. As illustrated above, the mainframe, battery pack, and functional module snap together to form a 500-MHz counter.

percent over the range of 0 to 540°C (Fahrenheit version also available). The digital DHS-8E with carrying case sells for $1595 while an older analog version, model HSA-8E, costs $600 less.

Wahl's other new entry is a digital heat-prober thermometer which uses a series of special thermistor sensors or platinum resistance probes to contact the area of interest. Model 392 operates from −50 to 500°C, while model 700 covers just the 0 to 100°C range. Accuracy is ±0.5 percent at 25°C, and the price is $395 for either model.

Perhaps your problem areas are hidden rather than hot. Viewing awkward, inaccessible areas is made much simpler with the new FS-100 Fiberscope from American Optical, Fiber Optics Div., Southbridge, Mass. This tool consists of two parallel fiber bundles in a 61-cm flexible gooseneck sheath, with a battery-powered "cold" light, and a wide-angle, fixed-focus objective lens. One fiber bundle illuminates the viewing area, while the other transmits a crisp image to the eyepiece. Neither heat nor electricity is introduced into the area being examined. The FS-100 comes complete for $295.

Microprocessors are contributing to the flexibility of many new instrumentation systems and portable gear is no exception. Witness the widespread success of personal scientific calculators. An even more recent example is Hewlett-Packard's model 3805A battery-powered distance meter that can automatically measure distances up to 1600 meters (one mile). After initial setup and balance adjustments to set the strength



Powered by two 9-volt batteries and priced at $115, the model 239 color-bar generator from Hickok Electrical Instrument Co., Cleveland, Ohio, provides nine basic patterns for television set-up and alignment work.

of the infrared reference equal to the return beam, distance measurements are continuously made and averaged by a built-in computer (microprocessor) and displayed on an LED readout. An appropriate reflector must be located at the far end of the line being measured. Normally mounted on a tripod, the $3395 instrument finds its primary application in outdoor surveying work.

Widespread adoption of microprocessors provides added convenience while presenting many new opportunities for remote servicing problems to crop up. Computer Product Service and Research Inc., Bluebell, Pa., recently announced model 0617B, a hand-held logic analyzer for just such occasions. Compatible with data rates up to 20 MHz, the 0617B measures, stores, and displays binary information on 32 LEDs arranged in two 16 "bit" rows. The memory and display can be arranged to present two independent 16-bit words, or a single 32-bit word can be presented. CPSR claims the $475 unit is valuable for debugging programs used in microprocessors. Most microprocessors go through several machine cycles before completing an instruction. The 0617B permits a clear view of logic statements in the circuit.

Another portable logic analyzer, also of recent vintage, is the MS-416 Mitscope from MITS, Inc., Albuquerque, N.Mex. Here 64 LEDs in four equal, parallel rows differentiate between logic ONE and logic ZERO voltage levels, while a variable time base (0.5 μs to 0.2 second) determines timing relationships. The $189.50 instrument also retains one-time-occurring pulses with a random access memory that first allows storage and then continuous display.

Much more complex and expensive tools are available for monitoring and troubleshooting binary data in communications channels. One such instrument, the model 601 Datascope developed by the Spectron Corporation, Moorestown, N.J., provides both a CRT display and a magnetic tape recording at the business machine interface (EIA RS-232C) of any standard modem. While the $7500 Datascope won't slip into your pocket, it can be connected to the data link directly or through a remote connection unit that bridges the EIA interface and provides electrical isolation without adding cable length or increasing electrical loading. Tape arranged in an endless loop format retains 25 minutes of traffic (before erasure). Of course, the cartridge may be changed at any time to retain a permanent record.

Toward serviceability

Built-in calibrating and self-testing features are two ways of easing servicing problems. But digital circuits present unique problems

When a $1000 voltmeter goes out for repair or calibration thereby paralyzing a $100 000 automatic test system, the system designer's nightmare of small instruments controlling large, expensive systems has become a reality. Of course, the need to service parts is an inevitability as is some degree of unreliability. But as the demand for more complex and powerful instruments increases, so does the challenge to increase their reliability while at the same time decreasing the frequency with which they must be serviced.

That this challenge facing today's instrument designer is a great one can't be doubted. As one designer puts it, "It is tough enough to design an instrument to today's criteria of performance and miniaturization at a competitive price, without having to worry about such things as poor reliability and maintainability. Not that it can't be done. It is simply more difficult."

Difficult or not, through increased attention at the design stage where service and reliability engineers can work hand-in-hand with research and development engineers (through the reduction of the instrument's total parts count, and through clever packaging techniques), we're seeing more maintainable instruments being produced with higher reliability.

How has this come about? There are several marketplace pressures forcing the instrument designer to face the challenge. On the one hand, the prospective user of electronic instruments can usually choose from among dozens of similar-performance units, all within the same price range. Yet the life-cycle cost of an instrument can be, and often is, much greater than the initial acquisition cost, once one adds those costs due to repairs, calibrations, and the downtimes associated with these services.

Other key pressures on the instrument designer stem from the increasing invasion of electronic instruments into such nonelectronic fields as the chemical industry, biology, medicine, process control, agriculture, and the geophysical sciences, to mention just a few. Here, nonelectronic personnel, untrained in electronic instrument maintenance, are expected to operate instruments properly, yet are often incapable even of changing a burned out pilot lamp. This has led companies like Leeds & Northrup and Ballantine Laboratories, long suppliers of electronic instruments to nonelectronic industries, to provide in-plant training courses, year round, for instrument users and maintenance people.

As a matter of fact, instruments used by such unskilled personnel must necessarily be designed to be "foolproof" in displaying information. In the future, the microprocessor may well provide instruments with displayed information indicating some fault condition or the instrument's need of calibration. This would be useful for production-line testing, where workers are prone to believe in an instrument display's veracity, regardless of its status.

Roger Allan Associate Editor

Digital troubleshooting

Even though modern instruments are generally smaller in physical size than their predecessors, they are much more powerful in performance and contain quite a bit more circuitry to handle this extra performance. Much of this complex circuitry is made up of digital ICs and is consequently harder to troubleshoot than the less-complex analog circuitry of older instruments that could be checked out by the familiar volt-ohmmeter (VOM). This has given rise to a whole new generation of instruments built specifically for troubleshooting digital circuitry.

This is not to say that the traditional VOM (or its newer brother the digital voltmeter) is an anachronism to be relegated to the instrument burial ground. It continues to be handy for checking power-supply parameters and linear-IC voltages. Meanwhile, digital test equipment, which includes logic probes, clips, and comparators (and, in some cases, oscilloscopes) can be used to check on digital problems.

Cracking the case

Some instruments have access points, externally, to check digital and analog signal status without having to take the instrument out of its case. However, these are in the minority, and most instruments require the removal of the chassis from the case. How easily an instrument disassembles for service can be an important point, and varies in length of time—anywhere from a few seconds to several minutes—with the instrument's type and complexity. Many instruments, notably digital voltmeters and multimeters, incorporate "snap-apart" or "single-shell" case designs. In the former, top and bottom case halves simply snap apart. The latter approach has the instrument's circuitry sliding out of a one-piece case, on a track, while being mounted on one or two interconnected printed-circuit boards. In either case, dismantling is usually accomplished in no more than a few seconds.

With the increasing use of low-cost plastic cases, a trend can be seen toward using little or no metallic hardware (screws, nuts, bolts, etc.) for fastening the case. But critics of plastic cases argue that over a length of time, the plastic tends to deform (particularly with high-packing-density instruments where internal heat rise can be a factor), making chassis removal and re-insertion very difficult. Furthermore, critics insist that many plastic cases are poorly designed thereby losing any advantage in natural resiliency. And of course there can be no argument that plastic cases do not provide the shielding inherent to the metal case against radio frequency and electromagnetic interference.

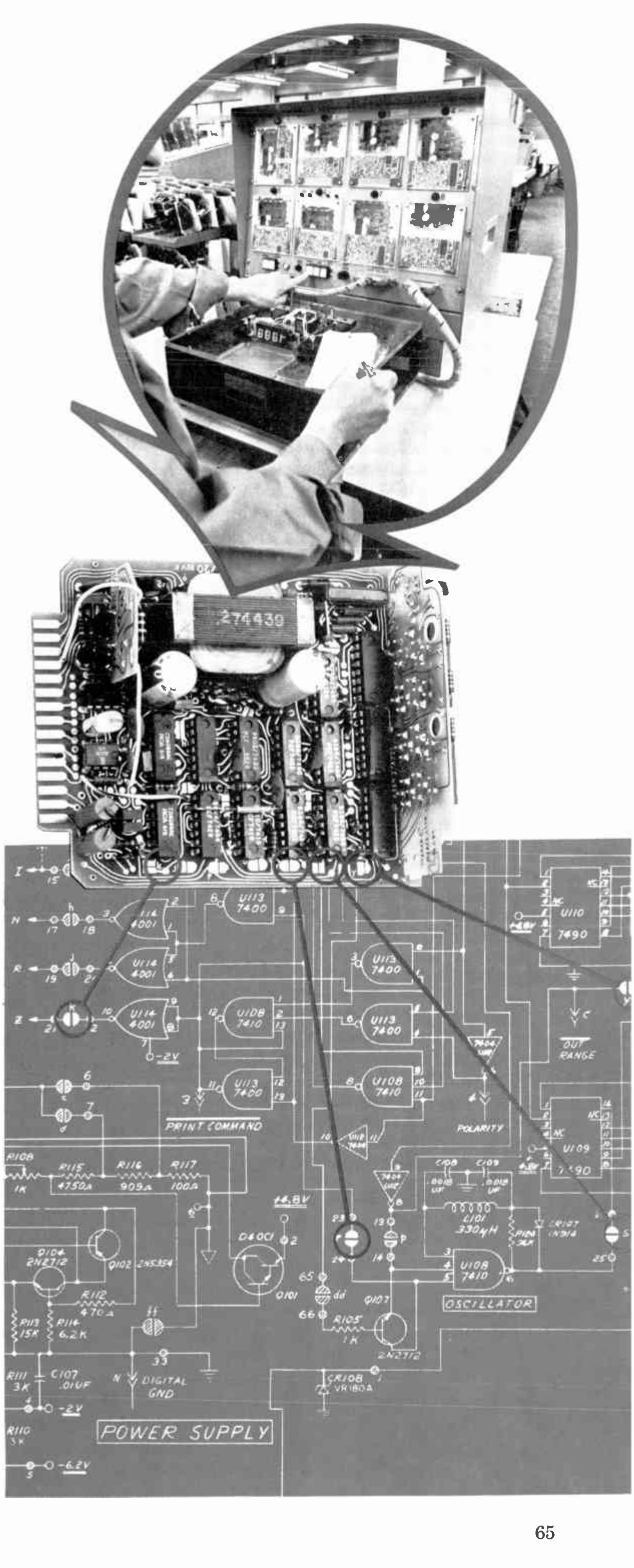
A look inside

A close examination of the insides of most instruments shows a tendency to group major subassemblies on different printed-circuit-board cards—power supply, front-end, display, and associated electronics, etc.—for rapid fault isolation. Some of these boards are interconnected to each other through flexible cable, flexible printed-circuit boards, or rigid right-angle connectors in a mother-board fashion. The flexible-connection method has the advantage of allowing instrument-circuit servicing without removal of circuit subassemblies.

The vast majority of circuit components—discrete, hybrid, and monolithic—are wave-soldered, thus reducing the expense of hand assembly. However, sockets may be preferable to soldering when it comes to ICs that, from experience, are known to be likely failure candidates—most often, those in the input and output circuitry. The trade-off, here, is between the expense of IC sockets that can often cost as much as, and sometimes more than, the ICs themselves, and the expenses incurred when unsoldering an IC from its board. And costs can escalate dramatically if incidental damage occurs to a printed-circuit-board conductor pad or the plating of a through-hole. Consequently, manufacturers that socket their semiconductors boast that the end item is easily serviced, hence economical.

Critics point out that, because sockets are a mechanical-contact medium, they are even more unreliable, not to mention the additional expenses (twenty 40-pin ICs in an instrument mean 280-pin non-soldered contacts) they can incur. In addition, a socketed IC is more likely to pop out of its socket due to shocks than a soldered one.

To combat the problem of printed-circuit-board conductor-pad (or rail) peeling during component unsoldering, Weston Instruments developed a "solder-bridging" technique that allows isolation of circuit areas without actually removing any components from the printed-circuit board. This technique (Fig. 1) is very useful in production since circuit input and output points, leads on op amps, etc., are brought out to "solder-bridge" pads, which are only interconnected (bridged by solder) as each circuit section passes production testing. Then, at a later date, a service



[1] The use of solder pads on the printed-circuit board, at key points, allows Weston Instruments to offer digital multimeters and panel meters that can be troubleshot rapidly, without the need to pull out any components, by unsoldering. All that is required is the unsoldering of the solder bridge joining the two pads, thus isolating any part of the circuit suspected of causing the breakdown. This technique was discovered by Weston during the production-testing phase of their instruments (top) where an operator is testing printed-circuit boards with unbridged solder pads. The boards are divided into eight major functional sections. Should a failure be present in any one of these sections, a light on the test console indicates which area it is. The next step is to bridge the solder pads, once the boards pass the test.

technician can check no-load circuit-component conditions, without the removal of a single component, by simply melting solder from the related bridging point on the circuit board. In this way, damage to the conductor rail and components from the heat due to unsoldering is minimized and longer component life can be expected. Servicing is much simpler and faster, of course.

Plug-in modularity

The concept of plug-in modules in instruments has been a popular one from the viewpoints of flexibility and economy. However, not all instrument designers agree that this concept is best when it comes to instrument calibration and reliability. With plug-ins, the use of additional connectors and sockets for mating different instrument subsystems means more inherent reliability problems. And it can also mean poor instrument performance due to erratic contacts and ground currents.

The plug-in concept does ease maintenance problems. By unplugging individual subsystems, access to an instrument's interior is facilitated, as is the localizing of problems to specific sections. Most instrument manufacturers equip their products with extender printed-circuit boards or flexible cables to allow servicing while the instrument is operational. However, not all do, and for those that don't, instrument servicing can be a headache.

The plug-in concept works particularly well in those instruments that utilize replacement of entire printed-circuit boards instead of individual components on the board itself. This is usually common on those instruments that have boards with mostly digital logic circuitry, such assemblies being comparatively inexpensive. And with the increasing use of digital ICs in instruments, it can be argued that maintenance by whole-board replacement is even more likely to be seen in the future as digital ICs become cheaper. Many instrument manufacturers currently incorporate this concept in their instruments.

There is another element to the whole-board replacement philosophy. More complex instruments are beginning to use multilayer printed-circuit boards for better packing densities of components (four layers is typical), and troubleshooting and repairing such boards when they become defective is usually costly and complex. Where mostly digital IC circuitry is in use on the board, replacing it becomes a more economical alternative to repair.

Self-testing and -calibration

The evolution of the microprocessor over the last two to three years has created some promising possibilities for instruments, not only in introducing true computational capabilities, but in providing these instruments with more self-testing and self-calibrating features to indicate when an instrument has an internal fault and is out of specification and calibration, and to take corrective action when in need of calibration. Self-testing and self-calibration can be initiated by the instrument operator either by the push of a front-panel button or by inserting a special printed-circuit card, with software, into a test socket, to allow the instrument to exercise itself through a diagnostic routine.

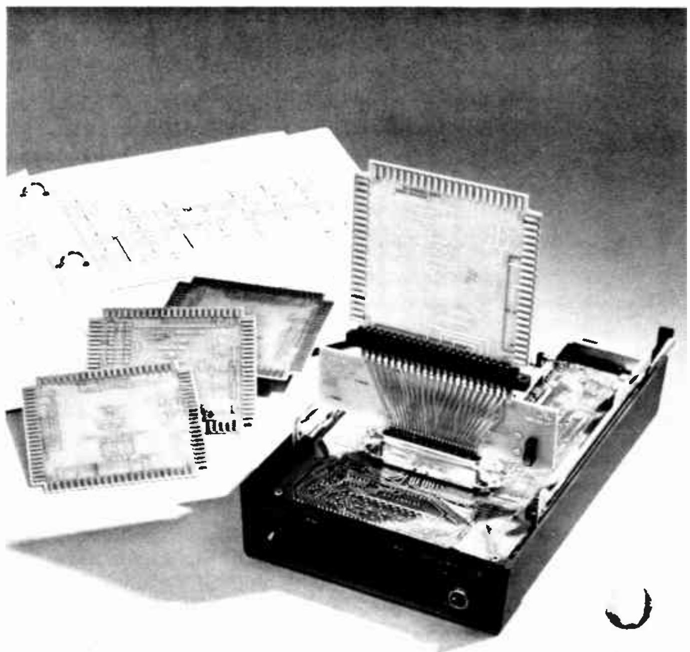
Hewlett-Packard has such a feature on its Model 3490A digital multimeter, which sequences itself through ten tests that validate the performance of the meter. On Hewlett-Packard's Model 5300 electronic counter system, diagnostic cards are available, as options, to exercise the counter through sixteen tests, for tracing circuit faults down to the component level (Fig. 2). On Ballantine's 5500A Autometronic counter/timer, a front-panel switch allows a 1-MHz "check" signal, derived from the instrument's main clock, to be applied to both input channels of the counter/timer. This frequency is displayed at a resolution that is automatically determined by the setting of the controls.

An example of self-calibration employing a minicomputer instead of a microprocessor can be shown in John Fluke's Model 7505 automated calibration terminal.* The system, which has ac- and dc-voltage transfer standards that are calibrated to primary standards at convenient intervals, uses a Digital Equipment Corp. PDP-11 minicomputer to generate error correction factors when the system is out of calibration. A printed output is also available to show the amount of error or deviation from an absolute value, and it can be used as well to observe an instrument's long-term drift behavior. Once the microprocessor becomes economical, Fluke feels that its use in general-purpose instruments for self-calibration, just as the PDP-11 is used in the 7505, can be realized.

The idea of self-testing is not new. Since the late 1950s, digital electronic counters have had "check" modes on their front panels. The autozero technique

* For further details, see Newcombe, C. B., "The automated calibration system—support requirements," *Proc. ISA-73 Annual Conference*, vol. 28, part 3, pp. 761-1—761-9, Oct. 1973.

[2] Self-testing of an instrument can be done with diagnostic software, as seen in Hewlett-Packard's Model 5300 electronic counter system. The optional plug-in diagnostic cards exercise the counter through sixteen tests, for tracing circuit faults down to the component level. A digital code readout corresponds to the faulty component.



used in most digital multimeters is another example of self-testing. No longer do technicians have to adjust an instrument for its zero point. This has been eliminated for them by those instruments that perform the zeroing with internal circuitry.

There is one self-test feature worth mentioning which is available on many general-purpose as well as sophisticated instruments. It involves checking the integrity of a multisegmented digital display by the push of a button or the turn of a switch on the instrument's front panel. The display is usually validated by having all of the segments of each digit light up showing the numeral eight. It is a well-known fact that the failure of a single segment in a seven-segment digit, for example, can cause erroneous readings of numerals six or zero, instead of eight.

Calibrations are fewer

Currently, there is a digital-instrument trend toward fewer calibration adjustments than were required for analog instruments of yesteryear. For example, high-performance oscilloscopes today require no more than 20 to 30 adjustments for complete calibration, compared to 60 to 70 such adjustments needed for oscilloscopes five years ago. The use of delay lines with m-derived designs, which in the past required an adjustment for each portion of the delay line, has been all but eliminated (Fig. 3). Newer-design frequency synthesizers require anywhere from seven to ten adjustments against about 70 such adjustments for synthesizers of 1969 vintage.

Of course, the use of digital ICs in designing these instruments has contributed largely toward this reduction in adjustments. The use of pulse-width modulation (PWM) design techniques has meant no adjustments (once numerous and cumbersome) for linearity.

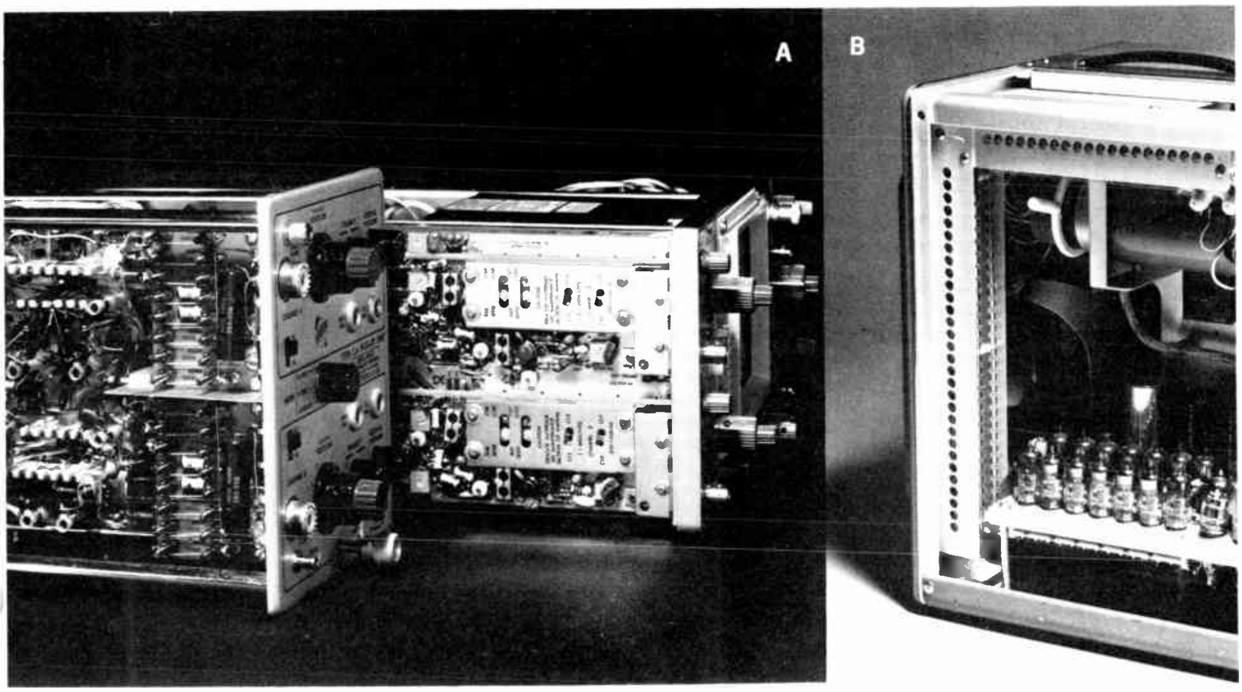
A good example of an instrument minimizing the number of adjustments is the Monsanto series 8500 electronic counter/timers from United Systems. This series of nine-digit universal counter/timers with up to 1-GHz measurement capability requires only a single adjustment—that of the capacitor in the quartz-crystal circuit, needed to pull the crystal in due to aging effects with time and temperature. The company also has the Monsanto Model 2780 4½-digit digital panel meter (DPM) with only two adjustments.

Even with fewer adjustments, today's digital instruments are more demanding in their calibration requirements than their analog predecessors simply because they are much more accurate. And in some cases where instrument miniaturization is overdone, the calibration job becomes even tougher.

While minimizing alignment and calibration adjustments can be considered every instrument designer's objective, some instrument manufacturers feel that such minimizing shouldn't be done at the expense of the design itself. Some low-cost instruments make use of selected-resistor values in place of adjustable ones to shave a few dollars off the final price tag, but the final price may be that which the instrument user pays when the instrument drifts out of specification and he cannot adjust it back simply.

Generally, most instrument designers feel, however, that the more an instrument is adjusted, the more likely it is to be in error in the long run. So the trend is toward long-term calibration intervals of six months or one year, instead of one to three months, and toward making calibration simpler. We can eventually expect calibration-free instruments.

[3] Fewer maintenance and calibration adjustments, and fewer components, are evident in modern oscilloscopes such as Tektronix's Model 465 portable unit on the right, a dual-trace, 100-MHz instrument, when compared with earlier 24-MHz, dual-trace, Type CA plug-in on the left (A). The older Model 541 oscilloscope used a delay line that required up to fifty "tweaks" or touch-up adjustments against none for the Model 465 (B).



Users grin and bear it

While this report deals largely with what manufacturers of instruments are doing to increase product reliability and improve maintenance techniques, the age-old problem of what recourse engineers, who receive defective or improperly operating equipment (or even equipment that fails during its warranty period), have is still very much with us.

Manufacturers actions in these situations are sometimes at odds with their stated policies of serving the customer. Most manufacturers' warranty statements are vague. Some state that defective equipment will be replaced or repaired within the warranty period, while many simply say nothing at all. Why shouldn't a buyer of a new instrument costing thousands of dollars be entitled to another new instrument to replace a defective one he never laid his hands on? Even more important, how long must he wait for a replacement unit or a repair to take place?

In surveying a broad cross section of instrument users (see the article on p. 69 of this issue), *Spectrum* found that users feel powerless to affect the quality of the instruments they paid for. Frustrations among users are particularly significant regarding the excessive lengths of time (weeks and months) it takes to get some satisfaction, either through replacement or repair. The result can be downtime costs many times that of the instrument itself, particularly with systems instruments. The fact that brand-new instruments can arrive defective raises questions about manufacturer quality control and workmanship. One user told us:

"We bought this $30 000 spectrum analyzer from a major and reputable instrument manufacturer two months ago. It hasn't worked a full day since. Of the eight plug-ins for the system, two were defective from the start, and two others failed within a week. One of the defective units was repaired a week later and failed again. It was repaired a second time. After finally getting the system to operate three weeks later, another malfunction developed that very day. We're still waiting for repairs to be completed."

Another user said, "I bought this $300 digital voltmeter whose power switch was broken after a few-days use. To avoid waiting a week for repair, I decided to replace the switch myself. A short time later, the voltmeter failed again, necessitating its repair by the manufacturer, who did not honor his warranty commitment, claiming that my replacement of the switch voided the warranty. I don't think this is fair."

Actually, there is something that prospective instrument purchasers can do. They can require that manufacturers supply them with reliability data for a meaningful evaluation. And users are sometimes guilty of patronizing certain instrument manufacturers despite previous bad experiences with the same manufacturer. If nothing else, a prospective purchaser should examine a manufacturer's performance, reliability, and warranty claims with extreme caution, and put the burden of proof on the manufacturer.

In fairness to the manufacturer, it should be pointed out that it is not as feasible to stock a $30 000 instrument for immediate replacement as it is a $300 instrument. Indeed, many manufacturers do replace such low-cost instruments that are defective.

Instrument manufacturers are also caught in the middle between their customers and component suppliers. Modern instruments no longer use many vacuum tubes and discrete transistors, components whose technologies have matured. Complex ICs are being used, many of which have just come into existence. As a result, no instrument manufacturer can easily predict, with any kind of accuracy and confidence, when such components might fail in the field, no matter how much pretesting is performed.

As for calibration instruments themselves, they are much more sophisticated than older ones. Today, instruments, such as Ballantine Laboratories' Model 6125A oscilloscope calibrator, provide an instrument user with a complete calibration capability in a small box, and with greater accuracy than the time-mark generators of the past—in fact, an accuracy that approaches that of the standards laboratory. The company has also advanced the state-of-the-art of accurate ac-voltage measurements with the recent introduction of a thermal-voltage converter (ac-to-dc transfer standard) that is usable up to a record 1 GHz.

Documentation is the key

One of the greatest aids an instrument manufacturer can provide his customer is complete documentation of the instrument for faster and easier troubleshooting of breakdowns. This not only means a schematic diagram of the circuitry, but also a complete parts list with standard replacements where possible (some instruments use proprietary parts that aren't replaceable quickly or easily), common-fault troubleshooting hints, waveform and voltage data on the schematic at key points, and a complete layout of the instrument's printed-circuit boards, showing all sides, with physical locations of the components.

While companies such as Heath, selling kit and wired instruments to a broad class of customers from neophyte hobbyists to scientists, have made it their business to provide complete documentation, it is quite surprising to see how many instrument companies are lacking here.

Another form of documentation is the video tape. Hewlett-Packard sells tapes to its customers to repair the Model 3490A digital multimeter. The tape is keyed to the 3490A service manual and shows how the self-test feature is used to isolate digital failures.

Tektronix also makes use of video tapes for instrument calibration and repair, but restricts their use to in-house training of its service personnel, believing that the usually complete documentation that accompanies its products is more than sufficient for the customer.

By placing inside the Model 168 digital multimeter's top cover a complete calibration procedure, a major-components layout, and maintenance information, Keithley Instruments gives an excellent example of how some manufacturers offer documentation simply and efficiently to a bench-top instrument.

It should be mentioned that documentation should not be restricted to providing service manuals and related printed matter. An additional function of documentation is to provide a complete network of service centers to service a company's instruments, quickly and at a reasonable cost.

What users like and dislike; need and can't get

Basic satisfaction with test equipment is tempered with a need for more self-checking, reliability, and human factors engineering

WANTED:
One inexpensive, easy-to-handle, superbly accurate, self-calibrating, multipurpose instrument.

Such is the aggregate fantasy of the user of instruments, as determined by a comprehensive *Spectrum* survey the details of which are described in the box below. Specifically, while most instrument users are reasonably content with the current breed of instruments that cross their work benches, they are at the same time demanding in their expectations of a future breed of instrument. For one thing, they see down time as reducible and accuracy as open to improvement. For another, they expect an ever-decreasing cost/performance ratio. Again, they may be pleased by the recent trend toward increasing portability, but they are far from satisfied with overall instrument design (human engineering). And finally, there are persistent complaints regarding documentation—be it product manuals, programming instructions, etc.—and field representatives. But first the good news . . .

Accentuating the positive

The vast majority of instrument users feel that the products they work with, day in, day out, are essentially satisfactory. They further look favorably on a variety of recent trends in instrument design. Portability has already been mentioned. Along with that, instrument users have been pleased with the increasing prevalence of solid-state and improvements in the number of functions available in a single instrument, in programmability, in ease of operation, and in stability, to mention just a few of their objects of praise.

Nevertheless, a healthy one out of six instrument users surveyed by *Spectrum* professed little or no satisfaction with their mechanized helpers. While a distinct minority, they must be considered an unacceptably large number of dissatisfied customers. And add to their complaints, the array of future expectations of the satisfied five-out-of-six and a vivid portrait emerges of the "rooms for improvement" in instrument design.

Evaluating the negative—reliability

While the vast majority of instrument users score their present instruments high in reliability when compared to those of the past—largely attributed to solid-state circuits including ICs—many users point out that instruments do not operate as represented and often do not serve the purpose for which they are intended. Early models have reliability problems. Most instruments are not rugged enough to withstand being carried in an automobile trunk. Very few instruments are built to withstand daily use by technicians. Many modern instruments are very reliable electrically but have poor mechanical designs that create unnecessary down time. And, although use of solid-state components has increased circuit reliability, this has been offset by the use of poorer quality mechanical components such as cases, switches, knobs, etc.

Add to the foregoing list of complaints another, closely related complaint voiced by many instrument users—that of excessive instrument down time—a costly problem which, they note, could largely be solved through modular construction, plug-in circuit cards, integrated circuits, built-in test and calibration capabilities, conservative design, decreased susceptibility to temperature fluctuation and mechanical vibration, protective devices for accidental overloads, adequate heat dissipation, and one other too-often overlooked, but vital process—quality control in production (or manufacture).

To many users, quality control is slowly getting worse, resulting in less operating time before servicing is required. Some even feel that many new instruments probably are not getting any quality control inspection. In general, most feel that workmanship is not what it should be or has been in the recent past.

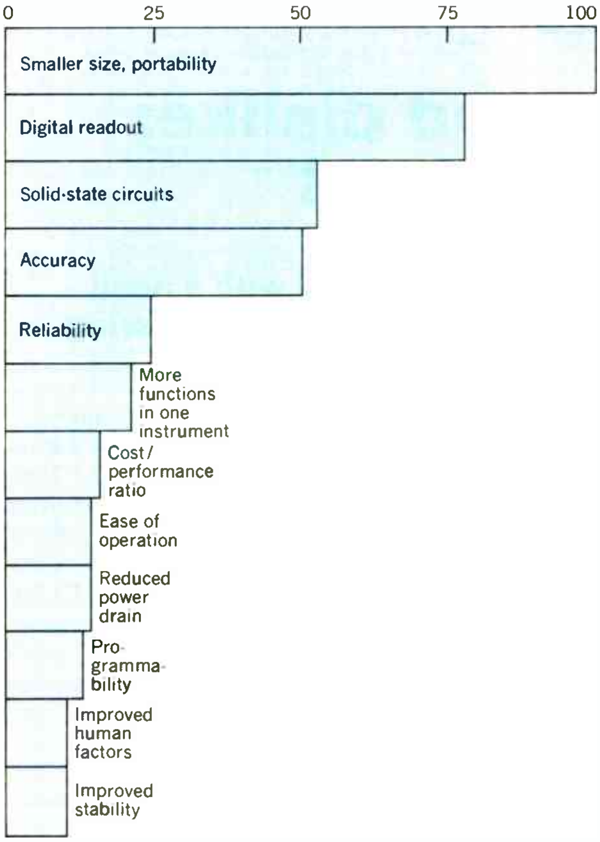
Evaluating the negative—human engineering

The second major area, already mentioned, of instrument user concern involves what can be termed poor human factors design—both in terms of everyday use and serviceability. While increased portabil-

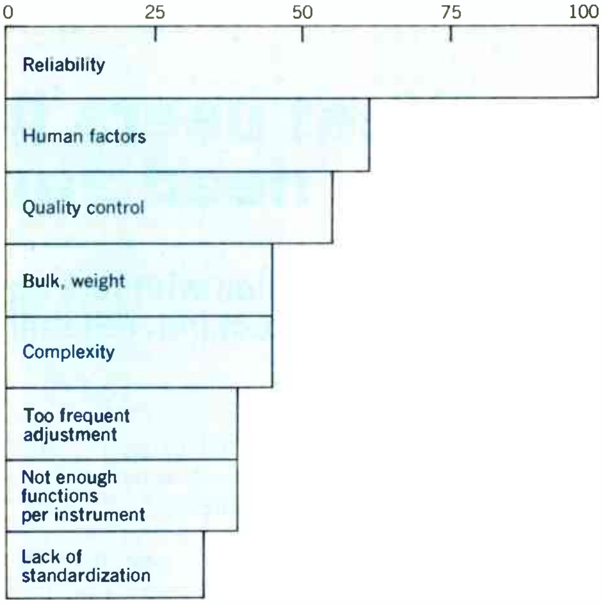
The basis for this report

To determine how instrument users rate the instruments they have purchased and use regularly, *Spectrum* undertook a comprehensive, 16-question mail survey of a random cross section of instrument-using IEEE members. The conclusions expressed in this report are drawn from the approximately 300 responses to the survey. Since the majority of questions in the survey were open-ended, calling for write-in answers, particular responses were neither predetermined nor encouraged.

Ronald K. Jurgen Managing Editor

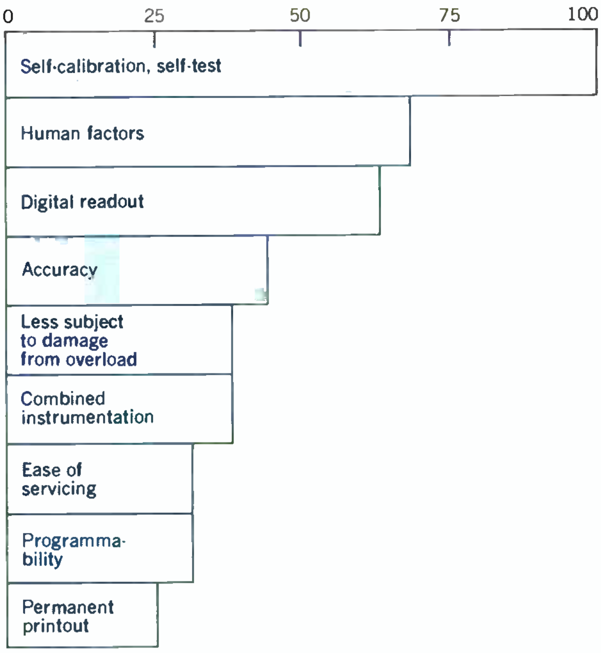


Smaller size and portability top the list of most-appreciated improvements in modern instruments compared to previous-generation test equipment. Other improvements got votes of approval in *Spectrum*'s instrumentation survey in the relative proportions shown.



Poor reliability is the most disliked feature of modern instruments with poor human factors engineering in second place. Other dislikes received mentions in survey responses in the relative proportions indicated.

Self-calibrating and self-testing features are what most instrument users would like to see in new instruments. Other features desired are related, in number of mentions, in the proportions shown by the bar plots.



ity over recent years may have lightened the user's load, he (or she) points out that operator/machine interfaces are often confusing or hard to manipulate. VOMs can be difficult to read, knobs may often be too small, panels too crowded, and function switches—following the unfortunate lead of recent television console design—too frequently relegated to the inconvenient rear of the instrument.

Other common complaints are that instruments have become too complex and "fussy" and too heavy and bulky; that they are not flexible enough to do more than one job; that they require adjustment too frequently to keep performance at top level; and that they lack standardization, particularly for interfacing, but also in such other areas as mounting provisions and control positions.

Manuals and field representatives

Similar difficulties have been encountered in regard to instruction manuals. The following are typical: early production models lack complete manuals; there should be a short-form instruction book to aid in set-up; the service manual is usually in the instrument repair department but is often needed when using the instrument; a separate and comprehensive operation manual should be fastened to the instrument somehow; more instructions should be printed on the case or inside the lid, and manuals furnished with instruments should fit inside the lid or cover; suppliers should provide a simplified users's manual to describe operation, particularly for oscilloscopes; and manuals supplied with instruments need to be improved to give more information on theory, use, and repair à la Heathkit manuals which are noted for their clarity and thoroughness.

As for field representatives, most users feel they do an adequate job in providing information or assistance in applying instruments. But a sizeable minority feel that field representatives do not know enough about how to apply the instruments they handle, that they don't know anything that isn't in the data sheets, and/or that they're generally not available when you need them.

Some near-future needs

One need that manifested itself in the *Spectrum* survey was a desire for better, faster permanent recording of measured data. A number of users suggested a memory/hold/recall capability, perhaps in the form of a tape that is integral to an instrument with a playback feature and hence could be used for recall at a later time. Another suggestion was for cassette recording and playback of a record of measured events and values. Yet another was for permanent printouts of digital readouts at low cost. And a quick and simple method of recording oscillograph traces, perhaps equivalent to the new Polaroid camera technique, was cited. Lastly, instruments with the ability to store one or two totally different operational settings were recommended. With a flip of a switch, in such instruments, one setting or the other could be obtained—e.g., in using an oscilloscope where different sweep speeds and amplitude settings are needed.

There was also some indication of a need for combined instrumentation of all types. A digital multimeter and an electronic counter was one combination recommended. A frequency meter and time-interval indicator or a frequency meter and digital voltmeter were cited. And a digital readout on the face of a conventional analog voltmeter was suggested.

Other features mentioned by users as desirable included: a capability of operating with 90-volt line voltages during brownouts; instruments that reduce operator error by indicating incorrect settings of controls and give warnings when parameters exceed specifications; longer-duty cycles on battery-driven instruments; simple calculator capability to manipulate data as they are displayed; and degree-of-accuracy readouts along with the data as part of the calibration procedure.

Instrument manufacturers take the floor

Instrument makers agree with the majority of conclusions in the survey but readily point out that they must always contend with a combined downward pressure on prices and an upward pressure on performance specifications. They also feel that many of the "dissatisfied" test equipment users, who say that they want an instrument such as the one "advertised" at the beginning of this article, are not realistic. Users are unwilling to accept the fact that tradeoffs must be made. Many of these same engineers, according to the instrument manufacturers, ultimately buy the least expensive instrument on the market that can do their measurement job and then are surprised to learn that they only got what they paid for.

Robert H. Brunner, marketing manager, Hewlett-Packard Instrument Products Group, says that the complaints all have some merit, but:

"We can't promise everyone a rose garden. The full-color/all-singing-and-dancing-machine that will solve all problems is as far off as ever, and one reason is the same as always: cost. Hopefully our engineers will temper their ingenuity with practicality, for these marvels have a habit of turning out to be about as useful as the proverbial handle with a mirror on one end, and a brush on the other.

"A certain amount of disappointment may always be the lot of the instrument-user who purchases on price, then evaluates on quality and performance. Test and calibration will continue to be a large part of instrument cost, so superficially similar instruments will probably continue to be vastly different in detail and performance. And some desires will continue to be incompatible. For example, compactness and portability, when needed, tend to be largely nonnegotiable, so something else must give. It's likely that will continue to be something like panel size or battery cycle time."

Jack V. Stegenga, product marketing engineer, Weston Instruments, is optimistic about the ability to meet demands for more functions per instrument. "An increased number of functions will continue to be available and the cost/performance ratio will definitely improve," he says. "When you need many functions, it is definitely more economical to purchase digital instrumentation of the latest design rather than analog instrumentation of older designs. We know this for a fact since we manufacture both types of instruments."

Harold Goldberg, president, Data Precision Corporation, however, disagrees that most instrument users really want more functions per instrument. He feels that the trend is toward dedicated instruments.

Reliability and downtime

Opinions on instrument reliability, according to Mr. Stegenga of Weston, will vary depending upon the type of instrumentation that the engineer questioned is in the habit of using. He says, for example, "I am sure that the standards-laboratory-type individual will state that analog instrumentation is more reliable than the electronic type. Undoubtedly, he still has, in his lab, analog-type instrumentation that could be more than 40 years old and still working properly. However, the field technician or maintenance man in industry could state that the new electronic instruments are better than the previous analog counterparts due to their better overload protection circuits.

"We happen to agree with both of these views," Mr. Stegenga states. "If an individual really knows his instrumentation and treats it properly, the mature analog-type instruments still have better life. However, if the individual is not all that careful and from time to time accidentally overloads the instrument, then the digital will give him better service. We definitely feel that within five to ten years digital instruments will improve to the point where they will equal or exceed the reliability of analog-type units in all respects."

Alan Peabody, marketing planning manager, Keithley Instruments Inc., stresses the fact that when you talk about reliability of modern instruments you should take into account their complexity. The typical instrument of 20 years ago, he notes, had about 12 active components and about 100 passive components. Today, a typical instrument has several thousand active components (even though they may be contained in just one or two ICs) and several hundred passive components.

Maintainability can certainly be increased by such techniques as modular construction, Mr. Peabody agrees, but that approach is not always cost-effective for relatively simple instruments. And built-in test capability might decrease, rather than increase, reliability even if it could be justified economically. Built-in, self-calibrating capability can be included as an integral part of an instrument, he states, but, again, is expensive. Calibration is usually done against a relatively expensive standard of some kind. It doesn't get any cheaper if you build it in.

Weston Instruments has included some self-checking features in certain of its instruments. For example, in some instruments, dc portions of the circuit can be checked by pressing a milliampere current button and then reading the millivolt drop across a shunt resistor to check accuracy and performance. Weston suggests to its customers that on other instruments that do not lend themselves to this approach, the customer might consider carrying an accurate resistor along with the instrument to measure the ohms circuit of the instrument.

Hewlett-Packard has recently introduced instruments that calibrate themselves, diagnose their own troubles, and calculate the information the user really wants from the raw measurement. But they don't sell for $99.95!

Human engineering, manuals

Most instrument manufacturers do not feel that there is any trend to placement of function switches on the rear of instruments. To the contrary, some of them tried doing so in the past, and then discontinued the practice in later instruments because they felt it was not good human engineering.

Satisfying instrument users with manuals seems to be a particularly thorny problem. Hewlett-Packard's Robert Brunner expresses the problem very well: "We've worked with operating instructions as brief as those on the back of our hand-held calculators and as complex as systems operating-and-maintenance instructions that fill a bookshelf. For instruments, the range is smaller, but we still are in search of a reasonable balance between adequate information just for application, and fully detailed service instructions. Some considerable success has been experienced with foreign-language translations containing only the material that's of interest to the *user*. It leads us to wonder: should we print those intimidating service diagrams, calibration instructions, and parts lists *separately*, for the maintenance people?"

Frank Elardo, product marketing manager, Tektronix, Inc., expressed these views on manuals:

"It is not always possible to have complete instruction manuals ready at the time of first instrument shipments, especially for complex products. In those instances, we provide an interim manual which is adequate for operating the instrument and performing incoming inspection front-panel checkout. A card is inserted in the interim manual to notify us where to send the complete manual when it becomes available. It is then provided at no charge.

"We do provide small operating manuals, particularly for our portable instruments. These fit inside the cover or the accessories pouch attached to the instrument. A service manual is also supplied that includes circuit descriptions, parts lists, schematics, and calibration and maintenance information. The operating instructions for most of our products are too lengthy to be printed on the covers."

Weston Instruments, according to Jack Stegenga, has included on the front cover of their instruction manuals a short-form instruction sheet on how to set up the instrument for initial use. And Keithley, among others, has printed operating instructions on instrument cases whenever feasible.

New measurement capabilities

An interest in combination instruments of many varieties was expressed in many responses to the survey and some of the instrument manufacturers chose to comment on such devices.

Alan Peabody of Keithley said that digital multimeters and counters, for example, have already been combined into one package but such combinations do not always make economic sense. It is not highly cost-effective, he says, to combine a high-frequency counter and a digital multimeter.

Frank Elardo of Tektronix cited the Tektronix TM 500 series, which includes digital counters, digital multimeters, signal sources, power supplies, signal processors, monitors, and even an oscilloscope, each in a plug-in, modular form. Combinations of these instruments can be plugged into a power mainframe which can accommodate either three or four of the units. All plug-in modules are connected in the power unit via a common interface board. Connections between modules can be made on the interface board providing a synergistic capability.

And just around the corner

In regard to the need for self-calibration and self-checking capability in the future, Mr. Elardo said, "It is possible that these functions will be accomplished through software by feeding a standard signal into a circuit and comparing the effect of the circuit on the signal to what it should be, then applying the necessary correction factor to the readout of the measurement. Thus, the readout would be accurate even though the analog display was in error."

There seems to be little doubt in the minds of instrument makers that built-in programmability is going to have a tremendous influence on future instrumentation. In fact, the means to the end for many of the new measurement capabilities that instrument users say they want may very well lie in programmability. For example, Alan Peabody of Keithley commented that programmability with microprocessors might very well be the way to get a degree of accuracy readout together with the measured value readout. And Howard Falk, pp. 46–51 in this issue, points out some of the intriguing capabilities for new measurements that are just over the horizon, thanks to microprocessors.

Detailed survey results

The summary of our instrumentation survey in this report has been necessarily brief, and general in nature. We are planning to make available at a future date a comprehensive listing of survey responses, question by question, for an as yet undetermined price per copy. Readers interested in obtaining more information about the detailed survey report may do so by circling number 129 on the reader service card.

The human factors

The operator, who must push buttons, twist knobs, and observe results rapidly, clearly, and unambiguously, is a principal design constraint

Although recorded attempts to integrate human factors into equipment design date back to the last century, it was not until World War II that human factors engineering became a specialized science. Today, instrument manufacturers consider "human engineering" vital in gaining user confidence as well as dollars. Indeed, many respondents to a recent *Spectrum* instrumentation survey (see pp. 69–72) regarded neglect of human factors a major problem in instruments they didn't like. Perhaps the greatest exponent of human factors engineering is NASA, which throughout the space program has conceptualized man as a working component of the overall system. In fact, NASA has defined a manned space system as hardware, software, and *man*!

Why human factors?

In any human-operated system, both sides of the man/machine interface must be considered for successful instrument design. Hence, the designer must make sure that (1) instrument operational requirements do not exceed human abilities, and (2) human performance tolerances permit optimal speed, accuracy, and performance. Those seeking to denigrate the role played by human factors in instrument design should remember that installing such features can reduce accidents, increase productivity, extend equipment life, and even make the difference between buyer acceptance or rejection.

An understanding of the body within the environment has provided scientists with many clues leading to more effective use of man interacting with machine. Over the years, research has given better understanding to such physiological phenomena as illusions, sensory adaptation and overload, perceptual organization, adaptation to darkness, retinal fatigue, flicker, and environmental stress.[1] Even now, studies such as those being conducted in Skylab are continuing to contribute to man's understanding of himself. The Apollo/Soyuz mission next year should enhance this knowledge.

A good example of the importance of understanding man–machine interaction was demonstrated in a recent study of the effect of background on color vision.[2] For years now, color television manufacturers have been experimenting with different types of "surrounds" for optimum three-color viewing. At least one manufacturer has based a whole line of TVs on the supposed superior qualities of dark surrounds as a background for its color dot phosphors. The study, however, reveals that a dark surround causes colors to appear *less saturated* (i.e., less "pure" to the eye) than when viewed with a light surround—even though (and perhaps because) the apparent *brightness* of the color is increased. If this is so, then the increased system contrast that is needed to obtain correct color reproduction with dark surrounds may not result in a higher *perceived* saturation to the viewer, even when actual *intrinsic* colors are increased in purity. Rather than increasing the spectral quality of their TVs, then, color manufacturers using dark surrounds have actually only increased apparent brightness at the cost of *lowering* spectral quality, a condition that can only be corrected by improving the system's inherent color purity.

This study is a perfect example of why human factors study is so important to instrument design.

What to look for

According to extensive studies conducted by NASA,[3] the following questions should be answered before designing a piece of equipment:

1. What sensory inputs does the operator use to monitor operations of the equipment? (Hearing, seeing, smelling, or feeling pressure, temperature, or pain?)
2. What discrimination is the operator required to make during the performance of his job? (Differences between audio tones, colors, dial indicators?)
3. What responses will the operator have to make while operating the instrument? (Lever pulling/pushing, knob twisting, button pushing, switch throwing?)
4. What movements will the operator make to operate the equipment? (Can he reach all controls? Will he be able to effect all control movements? Will the operation be fatiguing?)
5. What are the speed and accuracy requirements for operation? (Is speed or accuracy more important? Can the operator sustain performance?)
6. What work/rest cycles are required? (What are the effects of fatigue? What are the proper break intervals?)
7. What hazards are inherent in instrument operation?

These questions are admittedly general enough to include all types of equipment, including monitor/measurement/response systems that absolutely require man as a vital link in the system. For this reason, instrumentation designers would be primarily concerned with the first four human factors (the operator's sensory inputs, discrimination, responses, and movements), as well as the last (inherent hazards). Recent trends in instrument design have slowly eliminated a need for the fifth factor (speed and accuracy requirements) by virtue of automatic, semiautomatic, and memory-based routines, which have virtually transferred most speed and accuracy requirements

Marce Eleccion Associate Editor

from the human to the instrument loop. Factor six (required work/rest cycles), while applicable to instrument users in some instances (e.g., retinal fatigue caused by excessive CRT viewing), is normally more important for systems that require constant human scrutiny (e.g., radar operation or intensive-care monitoring), and even here the tendency has been toward more automatic operation, as seen in the recently installed BART rapid-transit system.

Because of the complex nature of man, human factors engineering problems are usually solved by a multidisciplinary approach, which allows not only greater flexibility but solutions that may be better than those obtained by individual and disjointed efforts (see pp. 75–77).

Divining the erring human

In general, human factors engineering can be looked at from the vantage point of man's sensory, motor, cognitive, and decision-making capability, or from the point of view of applications dealing directly with the human body. With respect to the latter, it should be noted that the trend has been to replace implantable sensors with contactless sensors, as shown by the progress being made with ultrasonic imaging and Doppler blood flowmeters.

A good technique for contactless testing of physiological parameters has been developed by Philco-Ford for future manned space vehicles. Using dry electrodes and a microphone mounted on a conventional chair, they have been able to obtain biopotentials (ECG), bioresistances (GSR, BSR, low-frequency skin-resistance changes, and direct current), bioimpedances (ZPG, ZCG, and respiration and blood pulse changes), and thoracic sounds. An immediate application of this technique would be in mobile heart-problem screening clinics similar to mobile X-ray units; paramedics could be used and data either stored or evaluated on the spot by computer programs.

Other techniques have been developed that measure practically every physiological function. For example,

- To measure motion and limb position for effective design of future spacecraft and control systems, Martin Marietta has developed a force-measuring system and limb-motion sensors that can be applied to the design of everything from fire-fighting equipment to underwater gear.
- To determine the effects of weightlessness, NASA is employing lower-body negative-pressure devices, limb-volume measuring systems, blood-pressure monitors, body-temperature monitors, vectorcardiograms, and metabolic analyzers. Useful in describing the ranges of "normal" body functions, such systems can be used to bring rapid and accessible medical diagnostic help to dispersed geographical locations.
- To test complex coordination, Langley Research Center has designed a system that can study performance under toxicological, physiological, and psychological stress.
- To study the environmental effects of vibration, noise, temperature, etc., on the human body, a system has been devised, by NASA, that may have the last word in determining passenger acceptability of future transportation systems.
- To diagnose visual problems, Ames Research Center came up with an automated visual sensitivity tester that not only spots visual dysfunctions and blind retinal areas, but can be self-administered via a film cassette.

Some human factors testing is so critical that complete test facilities have been set up to measure a range of parameters under varying conditions. Such is the case at the SAFEGUARD command and control test facility (CCTF) at Bell Laboratories in Whippany, N.J., which in essence is a human factors testing lab for evaluating the interactions between people and the semiautomated control system developed for the SAFEGUARD ballistic missile defense system. During a test, the operator's responses to CRT scenarios are both video-taped and recorded by computer, which interprets an action and simulates appropriate system responses. Besides testing, the CCTF can be used to demonstrate SAFEGUARD capabilities, prepare training movies, and provide hands-on training experience for operating personnel.

But what about instruments?

The large contribution to human factors engineering that has come out of such research centers as those of NASA may seem a bit esoteric as one looks at their original purposes, but many of the discoveries are beginning to find commercial and consumer applications. A case in point is a coaxial cable cutter that was developed for use under zero-gravity conditions. The tool proved to be so fast and accurate that it quickly became a commercial reality.

The need to understand what is required of an instrument in terms of human factors is aptly demonstrated in the case history cited on pages 75–77. After much time and effort developing the Tektronix 410 physiological monitor, the Tek R&D team found that anesthesiologists, using the instrument under practical real-time conditions, reported the EEG function to be less useful than the doctors had originally hoped. As a result, the EEG was totally eliminated on the later model 408, and replaced by a blood-pressure/pulse-reading monitor on the Tek 412 to fill the need doctors had of the EEG. In addition, the 412 has a dual-trace screen and an adjustable high-rate/low-rate/arrest alarm added.

Regardless of these later changes, the Tektronix 410 has been cited in an independent medical instrument survey as having performance characteristics superior to all other units tested. Further checking has revealed that the unit is considered by experts to be the first effective battery-powered unit of its kind, and is still in very wide use, surely a testimony to the effectiveness of integrating engineering, human factors, and industrial design.

What the Tektronix experience shows clearly is that no matter how deeply human factors are taken into consideration, the feedback loop to final instrument design is never really closed.

REFERENCES

1. Udolf, R., and Gilbert, L., "Behind the front panel," *IEEE Spectrum*, vol. 10, pp. 28–31, May 1973.
2. Pitt, I. T., and Winter, L. M., "Effect of surround on perceived saturation," *J. Opt. Soc. Am.*, vol. 64, pp. 1328–1331, Oct. 1974.
3. Behan, R. A., and Wendhausen, H. W., "Some NASA contributions to human factors engineering—a survey," NASA Technology Utilization Office report, Washington, D.C., 1973.

Building a medical monitor

In the fall of 1965, a group of industrial designers, electrical engineers, and mechanical engineers at Tektronix were called upon to form a team with the express purpose of building a medical instrument. Since it was to be Tektronix' first attempt to enter this market, not much was known about the problems of medical instrumentation and its related technology. This proved to have one advantage, however, since the absence of established rules and protocol governing the new project allowed its members to start completely from scratch. The result: a synergistic approach to the project task (see Box, this page) that led to an instrument superior to any that could have been obtained through disjointed efforts.

From scratch!

The Tektronix project began when one project member called the other participants together and suggested they work from the start as a team. After some debate about the wisdom of such an approach, the group agreed. Its core consisted of three electrical engineers, one mechanical engineer, and an industrial designer; soon after, the machinist assigned to the project became an active member as well.

Jim Gerakos Tektronix, Inc.

Synergy—a whole greater than its parts!

Webster's dictionary defines synergism as "cooperative action of discrete agencies such that the total effect is greater than the sum of the two effects taken independently." Buckminster Fuller defines it as the behavior of whole systems unpredictable by observing the separate parts.

A good example of a synergistic relationship is the chrome-nickel-steel alloy whose tensile strength is approximately 350 000 pound-force per square inch —100 000 lbf/in^2 greater than the combined tensile strengths of the component metallic elements.

Another example of synergy can be seen in combining members of different disciplines into an instrument design team, such as the project referred to in this article. The Tektronix team members strongly believe that combining their talents at the beginning of a project is many times more effective than calling upon them one at a time (as is often done in industry). In the past, Tektronix tried many combinations, including getting a team together when a project was partially finished or near completion.

The author is convinced that an instrument designed by a team on which three or more disciplines are represented is a better instrument. How much better is not measurable in simple numbers, but if readers were to look closely into the development of any tool or piece of equipment—electronic or otherwise—which they consider well designed, I will wager that a team effort was involved and that the teamwork made for better design.

The one thing all members of the project had in common was the fact that no one knew anything about the medical business. Together, they set out to learn. First, they made arrangements with a local hospital in order to have four of the team members observe the surgical area. This was the first of several visits to local hospitals, including conversations and correspondence with surgeons and anesthesiologists. After the first day in surgery, the four returned to Tek to compare notes and fill in the rest of the team.

Each of the observing team had seen a slightly different aspect of the total picture. For example, the industrial designer drew a quick sketch of the surgical area and noted several key items: the light level, placement of instruments and personnel, and the focus of attention—the patient. But taken together, their composite panorama was far more complex than what otherwise would have been isolated observations.

Strangely enough, the doctors themselves were not entirely sure what they wanted. They did come up with specific needs, however, and this list gave the team a starting point. The doctors essentially were looking for an instrument that could perform both as an electrocardiogram (ECG), with a wave shape to show alterations in the rhythm of the patient's heartbeat, and an electroencephalogram (EEG), to indicate the brain's electrical activity and show changes in oxygen supply to the brain. Further, the instrument had to be relatively small—since it would compete for space with heart/lung machines, artificial

[1] The Tektronix 410 physiological monitor.

Power plant controls: displays, computers, and man

From channel redundancy to direct digital control, new concepts in design are aiding the man at the power switch

Generating electric power reliably, efficiently, economically, and—not least important—safely, have always been the major objectives of public utilities. With much design and engineering effort recently devoted to nuclear power plants, the industry has been extremely alert to safety considerations.

A recent study commissioned by the Atomic Energy Commission (AEC) on reactor safety, released in August 1974, probably eased most of the tension that has been built up within and outside the industry, regarding safety aspects of nuclear plants. The study—"An assessment of accident risks in U.S. commercial nuclear power plants," supervised by Norman Rasmussen of M.I.T.—has concluded, among other things, that the likelihood of reactor accidents is much smaller than many non-nuclear accidents having similar consequences. And the likelihood of large financial losses, caused by nuclear-plant accidents was found by the team that conducted the Rasmussen study to be about 100 to 1000 times smaller than that of similar losses from other sources. The "Rasmussen Report" may provide a basis for reexamination of instrumentation philosophies for nuclear power plants. It is unlikely, however, that engineers and designers of nuclear power-plant instrumentation systems will slack off in their efforts to provide safe and reliable nuclear power generation systems.

In a nuclear power plant, the generally accepted distinction between the nuclear steam supply system (NSSS), including the nuclear reactor and all associated steam generating equipment, and the balance of plant (BOP) requires significant differences in instrumentation. While instrumentation in a typical BOP that includes pumps, compressors, auxiliaries, and piping can be encountered in many plants with process control, the NSSS instrumentation is mostly unique to nuclear power plants. This uniqueness is associated with different types of variables that have to be measured in the NSSS, like neutron flux within or outside the reactor or position of rods that control the reactivity, and also with specific requirements of reliability, accuracy, and operation under extreme environmental conditions (temperature and pressure, for example).

Redundancy, diversity, and separation

To design a reliable nuclear plant protection system, two major principles—redundancy and diversity—have to be observed. Redundancy is implemented by providing more than one instrumentation channel for each plant variable, while the diversity concept includes the use of more than a single plant variable to detect any condition that would require a protective action. A coincidence logic of "two out of four" may be used in such protection systems. This allows on-line checking and calibration of such protection channels, without risking a major reactor trip.

In addition, redundant safety channels must be *physically separate* from each other, to insure against total loss of a vital protection system in the event of a local fire or some other hazard. This physical separation principle can provide headaches to designers charged with control boards for nuclear power plants—for example, it is often very tricky to run hundreds and hundreds of cables within the control board without crossing cables. This complex topological problem can sometimes be successfully tackled by three-dimensional computer studies, as has recently been done by a Wolfe & Mann design team.

Human-engineered control boards

In recent years, much design effort has been directed at employing human engineering in the design of control boards for nuclear power plants. But there remains much to be accomplished in this area. Accord-

Gadi Kaplan Associate Editor

Reactor safety study highlights

According to the Rasmussen Report (Reactor Safety Study, WASH-1400, United States Atomic Energy Commission), the probability of accidents having ten or more fatalities is about one in 2500 per year per 100 nuclear plants. Put another way, this means, one such accident every 25 centuries. For accidents with 1000 or more fatalities, the chance is one to 1 000 000 or once in a million years.

A useful evaluation of nuclear reactor risks, can be made by referring to the following self-explanatory table from the report:

Annual fatalities and injuries expected among 15 million people living within 20 miles of U.S. reactor sites

Accident Type	Fatalities	Injuries
Automobile	4200	375 000
Falls	1500	75 000
Fire	560	22 000
Electrocution	90	—
Lightning	8	—
Reactors (100 plants)	0.3	6

ing to an article appearing last year in *Nuclear Safety* magazine, one can find, even in advanced plants, "controls that are difficult to operate, gages that are hard to read and confusing alarm arrangements."

But in fossil plants, too, there are cases of poor human engineering. Contradicting layouts of two adjacent switches—for example, the same position meaning "off" for one of them and an "automatic" mode for another one—are often undesirable. This reporter has also noticed a strip chart recorder with one pen that displays *three* variables related to the turbine. A switch from one variable to another is indicated by the pen returning to "0" position. Interpretation of the reading is consequently difficult even for an experienced operator, and one has to refer to another instrument to find out exactly which variable is being displayed.

Recently, there have been improvements: Consideration of man as a part of the overall control system has been gaining a wider public, and major companies consult control room operators when designing new control boards.

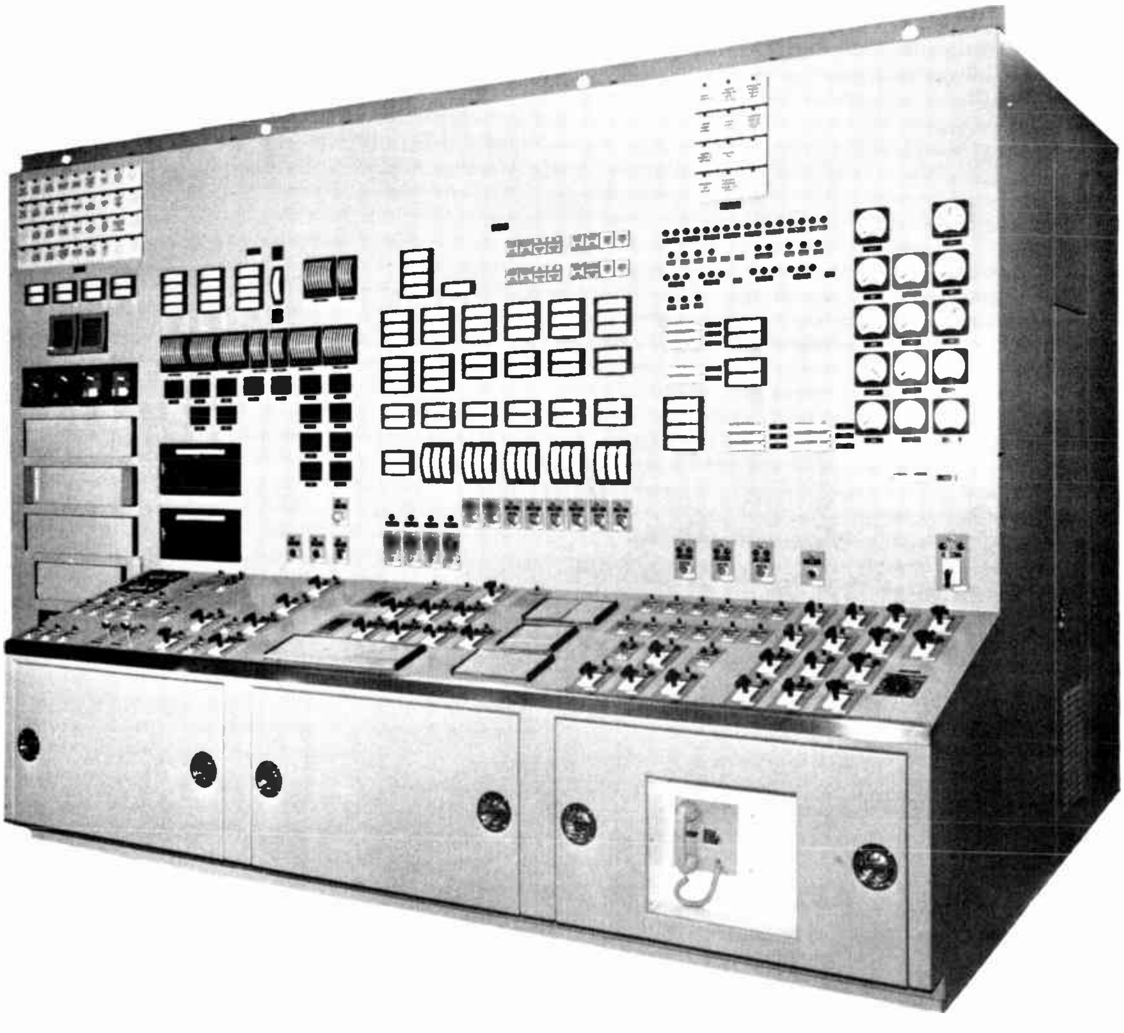
Nuclear plant control panels

The Nuclenet 1000 control complex for boiling water reactors (BWRs), designed by General Electric was introduced about two years ago. The GASNET control room system for the high-temperature gas-cooled reactor (HTGR), was recently introduced by General Atomic (GA) and presented to the October 1974 meeting of the Instrument Society of America (ISA). Both of these systems apply human-engineering concepts in their design.

Demonstrating a recent tendency to "think smaller," the developed semicircular console of the Nuclenet 1000 measures about 4.5 meters at the operator's side, compared to about 18 meters developed length of the straight conventional three-sided board. The width of the operator's working area on GE's Nuclenet 1000 is about 1.2 meters compared to 1.8 meters for a conventional panel. This reduction in area is mainly due to extensive use of color CRT displays that replace many conventional strip-chart recorders and analog meters. Another contributing factor to the slash in board size is the use of 3.8-cm^2 push buttons instead of conventional switches that had been previously used.

The Nuclenet 1000 is arranged in three "levels"—from bottom to top, operator controls, CRT displays, and annunciators. The most frequently used functions are located at the center of the board, whereas the lesser used ones are at the "wings."

[1] Part of the main control board of Consolidated Edison's "Indian Point No. 3" nuclear power unit, designed by Wolfe & Mann.



Functional layout and size-reduction are fundamental concepts in GA's control board prototype for the HTGR. GA uses 2.5-cm^2 push buttons and like GE's, GA's push buttons are back-lighted when activated. According to GA's designers, the slight eye fatigue that may be created by the irregularity in panel surface caused by light patches of activated switches is more than compensated for by a well-defined, unambiguous, and immediate grasp of plant control status offered by the back-lighted switches. Consideration of operator fatigue also dictates the selection of control panel color. In most cases, gray or green have been found satisfactory.

Various display philosophies

A growing practice in nuclear control board displays is the use of computer-controlled color CRTs. Different display modes are applied—bar graphs, trend graphs, schematic diagrams, or character display. A combination of the latter two is often used to display a subsystem graphically with indications of numerical values of its variables. The character-display mode is generally used for message displays, including alarm descriptions and operator instructions.

Various manufacturers, however, have different philosophies regarding the application of CRTs. All ten CRTs in GE's Nuclenet 1000, for example, as well as each of the six CRTs on GA's control board, can be assigned to display data from any subsystem of the entire power plant.

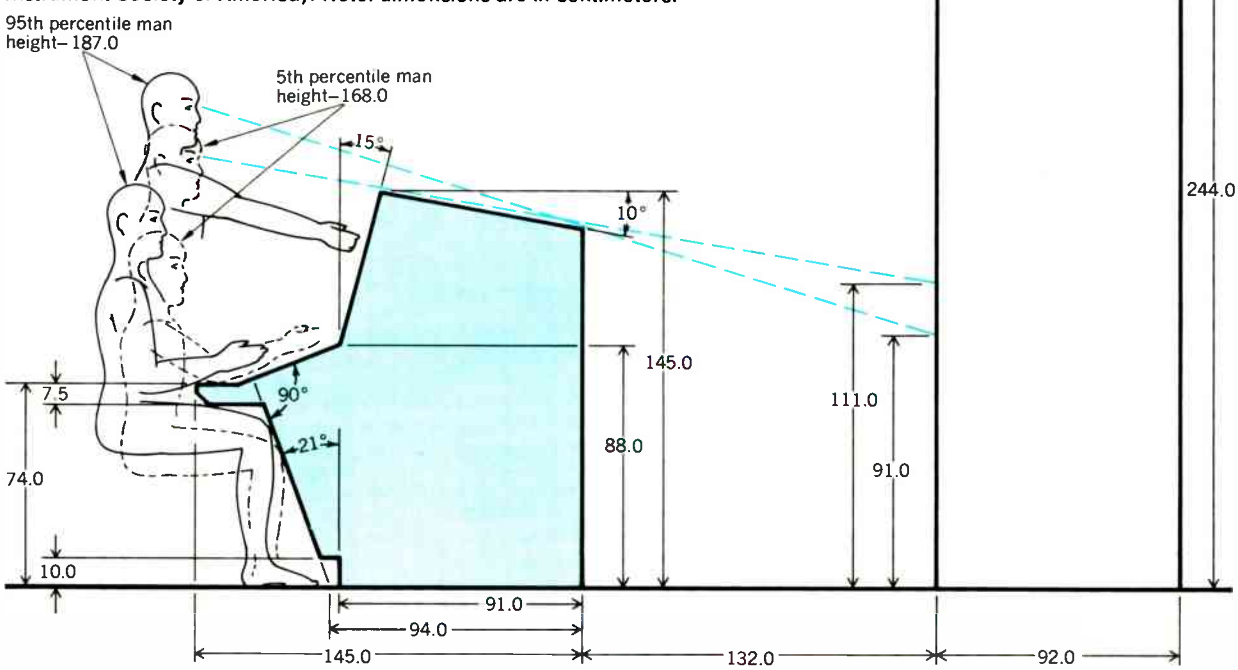
In a graphic control complex by Westinghouse, which has recently been proposed to various utilities, 11 color CRTs are incorporated. Eight tubes are located within the primary control center, whereas three other centers—safety, supervisors-monitoring, and engineer's console—have one tube each. Functionally, Westinghouse's display system provides alarming, status, and performance formats. One of the eight CRTs in Westinghouse's primary control center is dedicated to alarms, but another CRT is used as a second alarm, as well as a backup for the remaining tubes. Similar to control-room displays by other vendors, essential CRT indications in Westinghouse's system are backed up by hardwire indicators and annunciators.

A basic display system, comprising a minimum of two black and white, or (optionally) color, CRTs, is offered by Leeds and Northrup. In this system, the LN5000, one monitor is typically dedicated to alarm, and a second one is dedicated to alphanumerical utility display, like multipoint displays, group displays, or operator-guidance messages. A useful feature in many display systems is automatic ranging. This feature is extremely helpful in displaying variables with wide dynamic ranges.

The huge amount of physical data collected continuously from many sensors around a plant—neutron flux, flow, temperature, pressure—usually requires not only appropriate signal conditioning equipment, but also powerful computers capable of storing a sufficient amount of information. The stored information should also be continuously updated. Relevant data must also be immediately available for display. That this feature is essential for a dependable display is recognized by the manufacturers of display systems. But not only past information is displayed. L&N and GA, for example, provide users of their systems with software to display step messages for a complete plant start-up schedule.

To get the right portion of a message schedule or the desired variables on display, the operator has to

[2] Extensive human engineering has been incorporated in General Atomic's control panel for its high-temperature gas-cooled reactor (HTGR). (From a paper given in the 1974 International Conference and Exhibit, New York, N.Y., sponsored by the Instrument Society of America). Note: dimensions are in centimeters.



"tell" the computer his need, using an input device. Such man-machine communication is tackled differently by different vendors. While functional switches on keyboard devices are used in most plants, GA offers a light-pen input whereby the operator can "converse" with the display CRT more visually. The vendor suggests that pointing a pen at a lighted dot on a CRT may be somewhat faster than keying a full instruction code on the keyboard.

Averaging readouts

Besides CRT displays, straight digital readouts can often successfully replace analog meters and strip-chart recorders, particularly when the measured variable does not change enough to justify a trend recording (like the rpm of a turbine under a full-output, synchronized condition). One digital readout also can be used to replace several analog readings, particularly when the average of a few variables can represent sufficient data for the user. For example, GA uses this technique to display a temperature average of several thermocouple readings.

Multiplexing vs. hardware

The ever-increasing number of variables that must be monitored around power plants (nuclear and fossil alike) is already creating a major problem—how to run thousands of cables from the sensors to the control room in the most economical way. The typical total cable length needed for a light-water reactor can run in the millions of meters whereas the associated copper weight required is in the order of 100 tonnes! Another problem is how to run the cables reliably.

More control and instrumentation designers have recently been considering multiplexing as a viable technique to overcome these problems. Using multiplexing, thousands of signals can be transmitted over just one pair of wires, implying seven-figure dollar savings in raw material and installation costs. But some low-level, dc signals from sensors like thermocouples and pH meters need special shielding and conditioning prior to multiplexing. Protective signals, however, have to be hardwired, to meet necessary safety requirements.

Although multiplexing is considered advantageous by many vendors, there are skeptics, too. According to one vendor, "multiplexing has become a sort of buzzword many people use, but very few do anything about." Indeed, running three or four cables for each critical signal, while multiplexing other instrumentation channels, wherever possible, can be both economical and reliable. The reliability can be provided by continuous checks and calibrations on all the signals. A typical rate is once a second, as is the case in GA's system for the HTGR.

In the hardwiring of a vital system of a power plant, a failsafe mechanism is usually provided, whereby an accidental open circuit in a wire immediately triggers that part of the system into the safest operating mode under existing conditions. But in a hardwired auxiliary system that does not have a failsafe mechanism, an open circuit can even go unnoticed. Using multiplexing with continuous signal checking, a situation like this can be avoided.

Another multiplexing advantage over a hardwire concept is that an existing instrumentation system can be expanded at will—to transmit many more signals, excluding low-level dc ones, over existing wires—without having to run any additional cable.

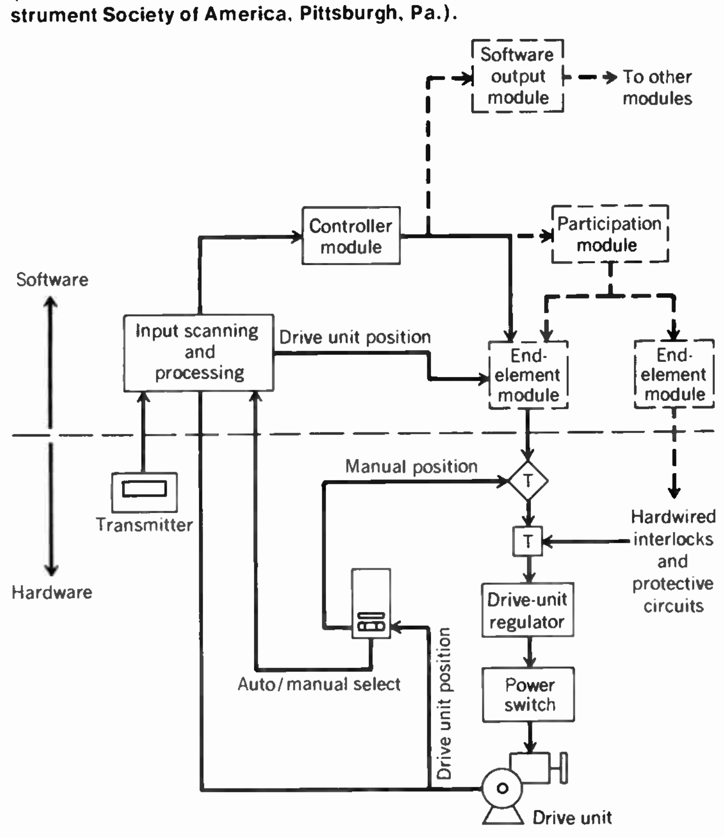
Termination cabinets—speed installation

Growing installation costs and the tight schedules demanded by power companies have forced instrumentation vendors to look for ways to reduce installation expenses. The "termination cabinet" concept, now used by most control board vendors, permits wiring of all field cables to terminal boards within the termination cabinets prior to control board shipment. These cabinets are supplied by the vendors and located in the vicinity of the control room. The next step is the full installation of the control board, including a hook-up of the board via factory pre-tested cables, with plug-in connectors to the termination cabinet.

Serviceability, maintainability, obsolescence

Designing an instrumentation system that will perform reliably is one thing; providing for serviceability is another. Though most systems are designed to be serviceable under load conditions, there are exceptions. In one fossil fuel plant, for instance, unplugging one card from a hydraulic control cabinet for inspection tripped the whole plant. Undesired plant shutdown can sometimes occur just by accidental shorting of two test points on a printed card being checked

[3] A typical direct digital control loop in a fossil-fueled power plant. A selector permits interlocking the drive-unit regulator via hardwire to protective circuits, bypassing the computer control. Leeds & Northrup's LN5300 control system controls many loops of this kind in "Martin's Creek" Units 3 and 4 of the Pennsylvania Power & Light Company. (From "Instrumentation in the power industry," vol. 17, Instrument Society of America, Pittsburgh, Pa.).



"on line" by a technician. A more "servicing-oriented" printed card layout could solve this problem. On the other hand, redundant instrumentation channels could provide their users with safe "on line" checking, testing, and calibration.

The Achilles' heel of present-day power plant instrumentation systems is obsolesence. With the fast pace of semiconductor technology, equipment sometimes becomes obsolete even before installation, let alone within an expected 30 to 40 years of the plant's active service. Many plants that include instrumentation purchased before 1970 still use old-fashioned relay protection circuits, whereas equipment now being designed includes solid-state protection circuits. In one plant, faulty printed-circuit cards of one system that employed flat-pack integrated circuits (ICs) could only be replaced after layout modifications required to accommodate a substitute IC. The flat packs are simply not made any more.

Continuity of production of the various components used in instrumentation systems is indeed a major concern of large utilities. Aware that it is impossible to be sure a manufacturer won't go out of business or discontinue production of a specific device, such utilities sometimes make it a point at least to secure a sufficient amount of spare components and parts for all vital systems.

Computer role

In U.S. power plants, computers were initially assigned, for the most part, to "passive" tasks—data acquisition, dynamic analysis and efficiency calculations, data-logging and storage, and, more recently, the control of displays and printouts of alarms.

But in fossil plants, computers have recently been successfully applied as well in direct digital control (DDC) of the power generating process. One such example is the application of Leeds and Northrup's LN5300 system in "Martin's Creek" Units 3 and 4 of the Pennsylvania Power & Light Company. The system provides direct digital control of boiler and turbine, in addition to data acquisition, storage and monitoring, and the control of CRT displays of alarms and operator guidance.

In Canada, DDC has also been applied successfully in nuclear power plants. One such example is "Centrale Nucléaire de Gentilly" in Quebec. The 250-megawatt plant employs three computers—two of them are interconnected and control practically every loop in the plant—from absorber rod position to steam drum level. The only systems that are not tied to the computer are the safety systems. The third computer is used for operator training.

In the Maine Yankee nuclear plant (Wiscasset, Me.), on the other hand, the computer that is one part of Combustion Engineering's instrumentation for that plant is assigned to monitor the motion of the core's control element (rod) assembly (CEA) and the rods' positions for deviation from procedural limits, as well as for actuation of computer-controlled interlocks, unrelated to safety systems. Apart from these functions, the computer in Maine Yankee is used for data logging and steady-state and transient analysis of reactor core operation.

Among various computer techniques employed in nuclear power plants is the "split task" and "shared hardware" mode of computer operation, suggested in Westinghouse's system. According to Westinghouse's scheme, the entire plant analysis and display control job is split between a "display" and a "result" computer, both sharing a common "memory pool." In the event of a failure of the vital display computer, the result computer takes over the display function. A computer redundancy is thus provided for a vital system, with a significant economic advantage over systems using complete computer redundancy—at no time is there an idle computer, and the entire volume of data processed by the system at any time, or the "throughput," is significantly increased.

In spite of sprouting computer applications both in nuclear and fossil-fueled power plants, the pace of the current trend is considered too slow by some engineers. The power industry was recently criticized by a senior instrumentation and control engineer as "re-inventing the wheel," as far as computer applications in nuclear power plants is concerned. Accumulation and evaluation of a vast amount of plant-operation data is vital, in his opinion, for future designs of nuclear plants. And this can only be successfully tackled by extensive computer use.

A major reason for the reluctance on the part of some design engineers to use computers for DDC in nuclear plants is the reliability problem, particularly software reliability. As one design engineer put it: "Hardware reliability is possible to grab hold of. You can build a system with redundancy and backup to computer hardware. But software? Software doesn't 'fail' like hardware does. The initial built-in bugs in the design are very hard to find." Although software houses may strongly disagree with this statement, they would probably admit that software debugging is indeed a major problem. But the successful Canadian example of computer-controlled nuclear plants, gives hope for more automation in nuclear plant instrumentation.

For further reading:

The basic guide to instrumentation in nuclear power plants is the *Nuclear Power Reactor Instrumentation System Handbook*, by Joseph M. Harrer and James G. Beckerley, a publication of the United States Atomic Energy Commission (USAEC). Those specifically interested in reactor safety can find useful information in the draft of *Reactor Safety Study*, issued by the USAEC in August 1974. Appendix III of that draft deals with reactor failure data. A discussion of the human factors in the design of control boards for nuclear power plants is presented by M. H. Raudenbush in *Nuclear Safety*, vol. 14, Jan.-Feb. 1973, pp. 21-26. Criteria for protection systems for nuclear power generating plants are stated in the IEEE Standard No. 279, which was revised in 1971. Developments in computer applications for fossil power plants are discussed in a section in "Instrumentation in the Power Industry," *Proceedings of the 17th International Power Instrumentation Symposium* (May 1974) of the Instrument Society of America (ISA). Government and industry requirements for nuclear balance of plant (BOP) instrumentation are discussed in D. L. Browne's article "Control system design for nuclear power," in *Instrumentation Technology*, Sept. 1974.

New measurement capabilities

The '74 designer's arsenal bristles with smart 'scopes, multipurpose meters, and high-speed digital analyzers

What do transient recorders, digital logic analyzers, and so-called "smart" instruments have in common? They're all instruments of the Seventies, fulfilling the need for new types of measurements. Together with traditional instruments that measure time, frequency, voltage, current, resistance, and capacitance, which have been vastly improved in detail and measurement ability, the new instruments provide the engineer with new dimensions in measurement capability.

Instrument advances have been largely fed by the explosive growth of semiconductor IC devices, themselves in need of advanced instruments to quantify device developments. Advances in microwave components, hybrid ICs, and traditional passive components have also been factors. Not to be overlooked are innovative design techniques, offshoots of newer devices and components. The result has been oscilloscopes with computer intelligence and signal sources and time and frequency instruments that have set new standards in performance. Even multimeters can now measure capacitance, power level (decibels), time intervals, and temperature, besides the usual voltage, current, and resistance parameters.

A clear trend in instrumentation is toward automating the measurement procedure, and to that end, some instruments have been so automated that they no longer fit the popular concept of an instrument. The operator has been relegated to the secondary role of pushing or twisting a few knobs and switches, and watching the measurement results on a display.

From computers to microprocessors

When Tektronix introduced its Digital Processing Oscilloscope (DPO) in the early part of 1973, a milestone was reached in computer-aided oscillography. The DPO was linked to an external minicomputer (a Digital Equipment PDP-11 unit) which massaged and analyzed the digital data that was produced by the DPO's processor. For the first time, an oscilloscope could, by signal averaging, make use of a minicomputer's computational power to extract signals buried deep in noise; display a signal in the frequency domain by a Fourier transform calculation; display a signal after passing it through an arbitrarily constructed digital filter, one that may not even be realizable with conventional components; compensate for an oscilloscope's nonlinearity and impedance-mismatch errors, thus providing a more accurate display; and scale the waveform to another form, such as a logarithmic frequency scale, for example (Fig. 1).

Availing the oscilloscope of computer power did not start with Tektronix's DPO, however. E-H Research had an oscilloscope (its AMC-1000) several years earlier that made use of internally hardwired logic for computational capability. Its stand-alone repertoire was, of course, limited, since it did not have the additional power that an integral minicomputer could supply (however, a standby computer interface was provided). During the second half of 1973, Dumont unveiled its 3100 system—a fully automatic, 100-MHz oscilloscope. Mated to an Interdata Model 4 or 70 minicomputer, it was the first real-time oscilloscope that allowed direct waveform analysis (instead of sampling the signal) all the way down to dc.

These computer-related oscilloscopes set the pace for Hewlett-Packard's recent introduction of the first oscilloscope with a microprocessor—the Model 1722A, 275-MHz oscilloscope at $4500 (Fig. 2).

[1] The most powerful oscilloscope yet built is Tektronix's Digital Processing Oscilloscope (DPO). With a Digital Equipment PDP-11 minicomputer, the DPO can perform a variety of signal-processing applications such as calculating the convolution, correlation, and fast-Fourier-transform functions of information displayed on the screen. It is interfaceable with many peripherals including calculators and the company's R7912, 1-GHz transient digitizer.

Roger Allan Associate Editor

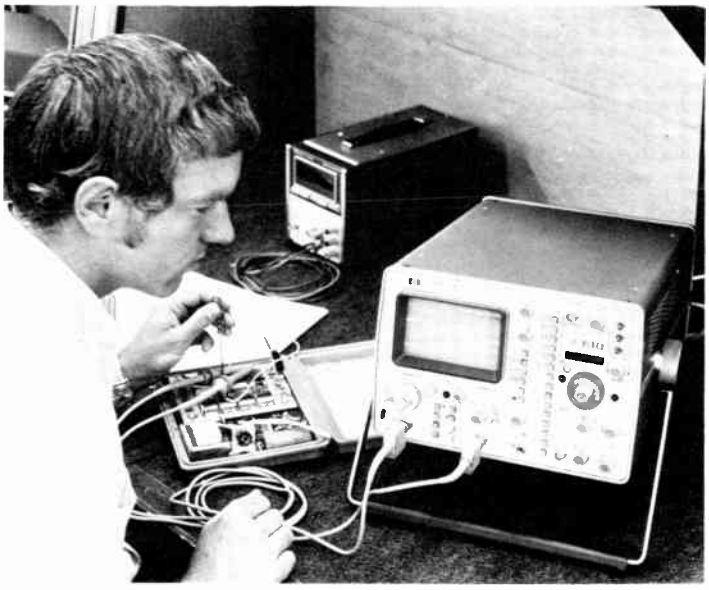
The significance of the 1722A is not so much its lower price (many critics think that $4500 is still too high a price for an oscilloscope) as the fact that it is the first self-contained, portable oscilloscope that provides the convenience of direct measurement calculations with a digital readout in the same package. No interfacing to any external and bulky equipment is needed. One of the things this oscilloscope can do is to provide direct digital readout of time interval, frequency, dc voltage, instantaneous voltage, and relative-amplitude (expressed as a percent) of signals on the oscilloscope's CRT, at much better accuracies or resolutions than were available.

A particularly convenient feature for measurement on the 1722A is the instrument's dual-delayed sweep, which allows the operator to display both start and stop points of a time-interval measurement as intensified markers. This has advantages over conventional single-delayed sweep methods in that it automatically eliminates errors due to vertical and horizontal drift and increases trace-positioning resolution. It also eliminates manual zeroing of the display, obviates the need for graticule line references, permits simultaneous viewing of two events separated in time while maintaining their timing relationship, and allows the presetting of the desired time intervals in the oscilloscope's digital display.

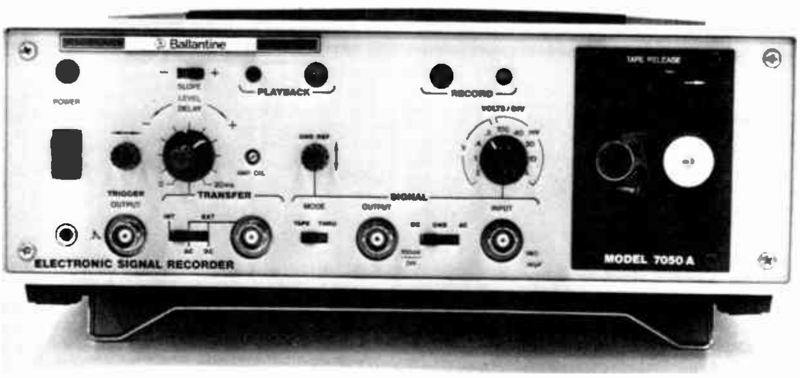
While much attention is being focused on the use of the microprocessor in oscilloscopes for simplifying the quantitative readout of measured parameters, this capability is not necessarily limited to microprocessors. Last year, Phillips Instruments unveiled a 50-MHz, dual-trace oscilloscope that allowed the instantaneous multiplication and display of the two input signals—no earth-shaking development except that multiplication could be performed on 40-MHz signals. The key was the development of a high-frequency analog multiplier IC that could perform accurate multiplications at such frequency levels. Phillips' latest oscilloscope, Model 3265, is a 150-MHz, dual-trace instrument that has just pushed this multiplication capability to 100 MHz. The 3260 series design lends itself to future programming, due to cold-switching of the front-panel controls.

Bandwidth is the name of the game

Two diverging trends appear to be taking place in oscilloscope design. At one end of the spectrum, there are powerful computing-type oscilloscopes, such as the DPO from Tektronix, that can be operated entirely in a closed loop, where the CRT display can be left out and the operator need not participate in the measurement procedure save for the manipulation of a few controls. In such a case, oscilloscopes can no longer be called by such names and are in reality automatic measuring equipment. The other end of the spectrum includes the general-purpose oscilloscope that is being improved in detail (but not necessarily in computational power) for less ambiguity of operation, smaller physical size, and lower cost. Oscilloscopes built for service and field work fit this category. Between these extremes fall laboratory-type oscillo-



[2] The first oscilloscope with a microprocessor circuit is Hewlett-Packard's Model 1722A. This 275-MHz instrument allows the direct calculation of time interval, frequency, dc and instantaneous voltage, and relative amplitude (in percent) of any signal(s) on the oscilloscope screen. Results are displayed on a digital readout, at much better accuracies or resolutions than were ever available in real-time oscilloscopes.



[3] Ballantine Laboratories' Model 7050A electronic signal recorder (below, left) makes use of an inexpensive loop of computer-grade tape (below) that records transient signals up to 100 kHz (at a 3.6-μs rise-time limitation). Indefinite-storage capability allows the replay of captured transients, on any oscilloscope screen, at any time.

scopes with improvements in measurement convenience, either within the same package (as in Hewlett-Packard's Model 1722A) or in separate but compatible modules (Tektronix's TM-500 line of oscilloscope modules, for example).

Notwithstanding recent computational advances in oscilloscopes, the two benchmarks of performance remain bandwidth and sensitivity. Of the two, bandwidth is the more important, according to Oliver Dalton, Tektronix's manager of laboratory oscilloscopes. "If we look at oscilloscope advancements, we can see that progress in higher bandwidths has been more rapid than better sensitivities. Very high sensitivities of 10 μV per cm are presently limited in usefulness to medical, mechanical, and some electronic (low-noise amplifiers) applications," he explains. Tektronix has a Model 7904 real-time oscilloscope with a 1-GHz bandwidth at a reduced sensitivity of less than 4 volts per cm by direct access to the CRT (10-mV-per-cm sensitivity at a 500-MHz bandwidth with a plug-in).

For sheer bandwidth, nothing can beat a general-purpose sampling oscilloscope. It operates by translating high-frequency inputs to lower-frequency domains by sampling the input waveform. Many sampling oscilloscopes are similar in operation to real-time oscilloscopes from an operator viewpoint. In fact, several real-time and sampling oscilloscope plug-ins are directly interchangeable, giving the operator excellent versatility.

Sampling oscilloscopes are available with bandwidths up to 18 GHz, with Hewlett-Packard's 180 series using Model 1811A plug-in and the 1430C sampling head, and with Iwatsu's (marketed by Dumont) Model 5009B oscilloscope. Programmable sampling oscilloscopes are available from E-H Research and Systron-Donner. E-H's Model 1010 features full-scale time accuracy of 1 percent and spans time ranges of 0.2 ns to 100 ms per division. Voltage accuracy is 2 percent. It can accept up to 100 input probes and be daisy-chained into a larger system. Systron-Donner's Model 774, when used with the Model 770 automatic network analyzer, has full-scale accuracy of 1 percent and spans time ranges of 1 ns to 500 ms per division. This model accepts up to 100 input probes and has "search" and (like the E-H Model 1010) programmable "delay" capabilities. The "search" mode allows the operator to seek any signal automatically.

What can be expected of future oscilloscopes? "Certainly larger bandwidths, in real time, than the 1-GHz mark we're at," says Tektronix's Dalton. He points out, however, that direct-measurement CRTs are approaching their limits in bandwidth and that newer types must be looked at. Further, more digital data are beginning to appear on the oscilloscope screen, complementing the analog trace information. While Tektronix has oscilloscopes that display digital information on the screen, this information is limited to trace-amplitude and time. Additional parameters such as duty cycle, pulse width, and slope can be expected, either on the screen, or on the front panel.

CRT work is presently going on to increase current densities from the present 300 lines of resolution for a 5-inch-diameter CRT to about 1000 lines of resolution. Other efforts are directed at improving phosphor-material efficiency, building better deflection structures, and improving upon recent developments in post-deflection magnification (PDM). Lower operating potentials and shorter CRT lengths have been the result of PDM advancements. Investigations have been conducted into ways of differentiating between multiple traces on the same screen, by the use of multicolor phosphors, notably by Thompson-CSF.

Enter digital instruments

Until about five years ago, there were no such instruments as waveform, or transient, recorders and logic analyzers. The increasing use of digital ICs for logic functions in circuitry has rapidly brought about the need for such instruments. Waveform or transient recorders allow the capture and viewing of signals tens-of-megahertz fast, and time resolutions as narrow as 1 ns. Digital logic analyzers permit a look at digital logic states and timing relationships in any digital system, thus making it easier to troubleshoot faulty digital circuits.

One of the biggest advantages of signal-storage transient recorders is that they allow the recording of a selected portion of the signal, preceding the trigger point. This method of pretrigger recording eliminates erroneous recordings due to false triggering from noise levels. Variable-delay provisions allow the additional capture and viewing of a selected portion of the signal, after the trigger point. All this is done by digitizing the input analog waveform and feeding the digital data into a digital memory. In addition to digital outputs, analog outputs are available for output to other instruments.

The fastest commercially available transient recorder is Tektronix's Model R7912 transient digitizer that can acquire, digitize, and analyze signals at up to 1 GHz in bandwidth. This is done at a level of 4 volts per division. The instrument is basically a scan-converter storage tube that has a silicon-diode-array target. This target can retain information on a signal for as long as 100 ms. An additional memory is needed to hold signals for longer periods of time. In 1964, the Atomic Energy Commission at Los Alamos built a scan-converter that performed up to 2 GHz.

Information gathered on the R7912's scan-converter target can either be raster-scanned and displayed on a conventional CRT monitor, or it can be digitized and put into the additional memory for later use. The digitizing is done at a rate of 512 waveform samples in 5 ns. Because the R7912 operates as a triggered oscilloscope does, no pretrigger information is available.

Capturing fast transients is important in laser, atomic-fusion, particle-physics, and nondestructive-testing applications, to mention just a few.

A novel method of transient capture is employed in Ballantine Laboratories' Model 7050A electronic signal recorder (Fig. 3). It makes use of an inexpensive and small loop of magnetic tape that records transients from dc to 100 kHz, at a rise-time limitation of 3.6 μs. Transients can be played back, on any oscilloscope, for further signal examination, at 3000 divisions per ms with a 40-dB dynamic range. Because tape is the storage medium, storage is indefinite, and signals can be replayed at any future time.

Logic instruments

About five to six years ago, digital logic instruments in the form of pocket probes began appearing.

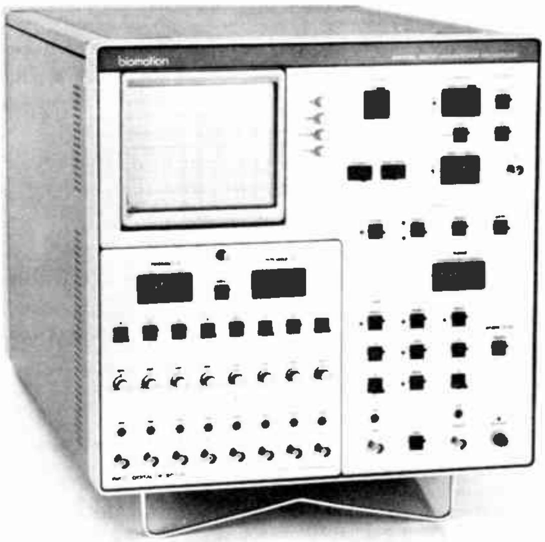
These diagnostic instruments displayed logic states ONE and ZERO by having either their lamps or light-emitting diodes light up or not. They sufficed for simple or static digital circuitry but were inadequate for resolving timing relationships in the more complex and faster digital circuitry of today (rise times of less than 1 ns are all too common). Newer and more sophisticated logic analyzers were thus born. Three of these are Hewlett-Packard's 1601L, Biomation's 8200, and E-H Research's AMC 1320. All have CRTs that display the digital data. Hewlett-Packard's instrument emphasizes state analysis while Biomation and E-H Research have made contributions to multichannel timing analysis.

Hewlett-Packard's 1601L logic state analyzer can collect data at 10 MHz and display it on a CRT, in truth-table format of ONEs and ZEROs, and in parallel data streams of 12 columns by 16-bits long. For ease of interpretation, the display can be formatted in octal groups of three, or BCD (binary-coded decimal) groups of four, to match the logic system being analyzed. The pattern trigger digital delay and display format make it ideally suited for analysis of state sequences such as microprogram analysis.

Biomation's Model 8200 digital logic recorder (Fig. 4), a more recent arrival than the 1601L, is the fastest digital logic timing analyzer to be built. It has the largest input data rate of any analyzer on the market —200 MHz. With it, critical timing relationships can be examined in up to eight simultaneous pulse trains. The high sample rate allows resolution down to 5 ns in width, and thresholds can be set to any desired level in 25-mV increments. An input latch feature allows the detection of 1-ns spikes.

E-H Research's AMC 1320 Digiscope is a 0.05-Hz to 50-MHz logic timing analyzer (ten decades with three time scales per decade) that can handle asynchronous data. Its dual-threshold detectors allow it to detect, anywhere in a digital logic stream, low-amplitude logic ONEs, high-amplitude logic ZEROs, signals with slow rise and fall times, and spikes as narrow as 5 ns. Up to eight input data channels are possible with a 100-word-per-channel capacity, using four dual-channel plug-ins. The main frame of the 1320 provides for as many as 16 input channels (with four 4-channel plug-ins). The instrument features combinatorial triggering (parallel word recognition), high-impedance active probes, and complete readout of all the instrument's settings on the CRT.

[4] Complex digital logic circuitry calls for sophisticated digital logic analyzers such as Biomation's Model 8200, an instrument capable of checking digital data rates up to 200 MHz. Up to 2048 bits may be checked simultaneously (or bit by bit), in each of eight pulse trains, on a CRT display.



Sophistication in time and frequency

Electronic counters have traditionally formed the spearhead for accurate measurements of time and frequency, either by direct counting for frequencies to 600 MHz, or by heterodyne or automatic- and manual-transfer-oscillator techniques for microwave counters that can measure frequencies up to 18 GHz.

The heterodyne technique in microwave counters allows the measurement of a carrier that has large, frequency modulation (FM) bands on it—an important advantage in communications work. The transfer-oscillator technique, as used in Hewlett-Packard and Systron-Donner's 18-GHz counters, limits the FM bandwidth to no larger than the phase-locked loop bandwidth of the transfer oscillator, but offers better sensitivities than the heterodyne method.

EIP's Model 351D, 18-GHz, heterodyning microwave counter (20 GHz, optional) offers improved sensitivities of −20 dBm over 0.825–1.1 GHz, −25 dBm over 1.1–12.4 GHz, and −20 dBm over 12.4–18 GHz. Sensitivity of −30 dBm over 1.6–6.5 GHz is optional. Of course, automatic-transfer-oscillator, 18-GHz counters such as Hewlett-Packard's Model 5340A offer sensitivities as low as −35 dBm.

While frequencies get higher every year, measurement techniques have been vastly improved to make possible sophisticated measurement of single-shot time intervals, pulsed radio-frequency (RF) signals, data bursts, and very narrow pulses. Automatic, computer-control operation is evident in many of today's time and frequency counters.

The newest measurement capability in time is provided by Hewlett-Packard's Model 5345A electronic counter that allows pulsed-RF signals to be measured both practically and precisely. Pulses as narrow as 50 ns can be measured (the limit had been about 1 μs) directly. This 500-MHz, 11-digit, 10-mV counter is fully automatic up to 4 GHz with the use of the 5354A plug-in. Additional plug-ins allow the measurement of 18-GHz signals. The 5345A counter can also make time-interval measurements of single-shot events to within 2 ns, and of repetitive time intervals down to 1 ps.

If you need an instrument that can resolve the smallest event in time, then the Monsanto Model 8330 time-interval counter from United Systems is the answer with its 100-femtosecond resolution by signal averaging (1 femtosecond = 10^{-15} second), bettering the 1-ps resolution of the E-H Research 142 and the 5-ps resolution (by signal averaging) that Hewlett-Packard offers in its 5360 computing counter. The United Systems 8330 offers single-shot resolution of 100 ps without signal averaging, while the Hewlett-Packard 5360 claims a "usable" resolution of 300 ps. To get some idea of how narrow in time a 100-femtosecond time interval is, it is the approximate time it takes light to travel one thousandth of an inch.

The Ballantine 5500A provides autoranging on even a single time interval with resolution of 100 ns without overflow. The 110-MHz counter uses a read-only memory to automate the positioning of decimal points and annunciators.

Just as frequency and time counters have been getting higher in frequency, better in accuracy levels, and more sophisticated in performance, so have signal sources—recipients of the same microwave-device breakthroughs (at the highest frequency levels) as wider bandwidth and more powerful yttrium-indium garnet (YIG) oscillators and more efficient impact avalanche and transit (IMPATT) diodes.

Microwave frequency sweepers are commonly available to cover bands as large as 2 to 18 GHz in a single sweep. The expanding mobile-communications field has meant an increase in the output-power levels required of signal sources, and very sharp frequency bands with little or no skirts. Such output power levels as 1 volt into 50 ohms are standard, compared to 100-mV levels just a few years ago.

Multimeters measure more parameters

Not very long ago, if you bought a digital multimeter, it meant you bought an instrument that measured voltage, current, and resistance, at best, in the same package. If you needed to measure true-rms ac voltage, capacitance, power levels, time, or temperature, you had to buy a separate instrument for each of these measurement parameters. That picture is beginning to change. You can now buy digital multimeters that measure several combinations of the aforementioned parameters, and at a price that is not much higher than you would have paid for a digital multimeter with fewer measurement parameters.

The ordinary laboratory impedance bridge has also gotten into the act. Added to the traditional compacitance and inductance measurements have been conductance and admittance measurement capabilities.

Jack Stegenga, Weston's new products manager, sums up the situation:

"Measurement capability for the design engineer today has meant that he needs only one instrument, at a lower cost, instead of four to five instruments for the same capability. Capacitance and decibel measurements are becoming easier to implement in multimeters and can be expected to be seen in more such instruments."

While the listing of such multimeters would be too lengthy for this report, here are a few representative examples of the most recent ones:

Data Technology offers a low-cost, 3½-digit multimeter, Model 20, that measures capacitance as well as ac and dc voltages and resistance. United Systems offers the Model 2180 digital multimeter that measures decibels from −60 to +60, in addition to ac and dc voltages and currents, and resistance. Systron-Donner's Versatester is a multimeter (ac and dc voltage as well as resistance), pulse generator, power supply, sine and square-wave source, and frequency counter, all in one package. Hickok Electrical Instruments, Valhalla Scientific, and California Instruments Co. all offer digital multimeters that double as frequency counters. Practically every multimeter manufacturer offers true-rms ac-voltage measurement as a standard or optional feature. Many offer four-wire resistance and ratiometric features.

An interesting new instrument is Tektronix's Model DM43 digital multimeter, designed to be used atop Models 465, 466, and 475 oscilloscopes. This multimeter offers measurement of voltage, resistance, temperature, and differential time-delay intervals. The temperature measurement range is −55 to +150°C. The time-delay measurements can be made between any two points on the oscilloscope screen.

What price accuracy?

Digital multimeters may be getting more versatile, but they may also be reaching their limits of resolution and accuracy for voltage measurements. A microvolt measurement is about where most digital multimeters (or voltmeters) stop in resolution. Submicrovolt-region measurements, it is pointed out by most instrument manufacturers, are not very practical because component noise levels are as big as, if not larger than, the voltage levels to be measured, except for some special applications. Accuracies to within 0.005 percent or better should be left for secondary standards, it is felt, and 0.01-percent accuracies are sufficient for the great majority of applications.

Some of those special applications involving low-level measurements include semiconductor-material processing. Companies such as Keithley Instruments provide meters than can measure nanovolts and picoamperes, for such applications.

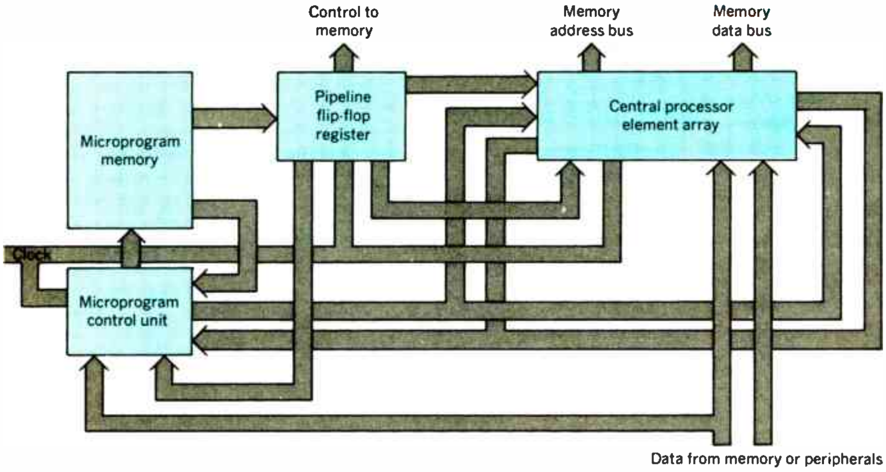
As for measuring current, a unique instrument is Weston's Model 670 FET-input volt-ohmmeter (VOM). It is the only known instrument that allows "in-circuit" current measurements, by direct contact. Designed to be used in checking printed-circuit-board currents in power supplies, it can do this without the need to open any of the conductor paths, by the use of a two-terminal probe set. The set consists of two individual probes that snap together at various spacings and can also be used apart. Accuracy of current measurement is within 5 percent. Until the introduction of this meter, clip-on, loop-type probes were the only instruments that could measure current without breaking a circuit path.

Despite the tendency to provide multimeters with more capability, the big revolution is in bringing down costs, not only for multimeters, but for all types of instruments. Harold Goldberg, president of Data Precision Corp., defines things further:

"There are two important instrument-market trends. A cost-conscious market, where a low purchase price is the most important factor, and a performance-conscious market, where complete systems performance and compatibility is paramount. I wouldn't be surprised to see a 100-MHz, frequency counter selling for as low as $300, as an example of the low-cost push."

Reprints of this 44-page Special Report on Instrumentation (reprint number X74-111) are available at $4.00 each. Please send remittance and request, citing the above number, to IEEE, 445 Hoes Lane, Piscataway, N.J. 08854, Att: SPSU. (Reprints are available up to 12 months from date of publication.)

Microprogrammed bipolar microcomputers are assembled from integrated circuit blocks



Pipeline computer system design using 3000 series bipolar circuit blocks.

The 3000 series of bipolar large-scale integrated (LSI) circuit blocks is designed to meet the needs of data control and communication systems for high-speed programmable logic. A Central Processing Element (CPE) and Microprogram Control Unit (MCU) are the key blocks. The MCU selects microinstructions from a high-speed microprogram memory in the order required to execute higher-level instructions. It contains all the logic for such selections, as well as several other functions that support CPE operations. One MCU is normally required per system, but any number may be used in a multiprocessor system.

Each CPE is a 2-bit-wide slice through the data processing sections of a computer. Logic functions and data paths are defined by the microinstructions stored in the microprogram memory. The CPE decodes the portions of the microinstruction words that govern its operations. Any number of CPEs or CP arrays may be used in a system.

To form computers with any desired word length, an MCU, several CPEs, and enough memory circuits to store the necessary microprogram words (microinstructions) are connected in the organization preferred by the system designer.

In addition to the CPEs and an MCU, the 3000 series includes: a 3003 Look-Ahead Carry Generator, which provides fast carry over a complete 16-bit arithmetic section (array of 8 CPEs); the 3212 Multi-Mode Latch Buffer, a general-purpose I/O (input–output) device, 8 bits wide, which provides storage and buffering functions; a 3214 Interrupt Control Unit, which provides eight levels of priority interrupt automatically interacting with the MCU, while an additional 3214 units can expand the interrupt subsystem to any number of levels; and the 3216 Bi-directional Bus Driver, a 4-bit-wide bus driver and receiver used to expand the data buses of very large systems.

Schottky bipolar memory circuits, with industry standard configurations, are available for microprogram development and storage. These include the 3601A 1024-bit (256 × 4) electrically programmable read-only memory (PROM), the 3604 4096-bit (512 × 8) PROM—an advanced design, with typical access times less than 70 ns, that allows the microprogram of a large, complex system to be stored in only three or four packages—as well as, the 3301A 1024-bit ROM, a metal-mask design, and the 3106 256-bit random-access memory (RAM) with three-state output.

The 3000 series devices are building blocks with variable data paths and logic functions, so there are virtually no restrictions on how the system designer organizes the blocks and logic operations.

The pipelined design shown in the figure uses a register of TTL flip-flops to delay microinstruction transmission. This allows microinstruction execution and fetch cycles to be overlapped, cutting the average microinstruction cycle time in half. In a non-pipelined design, the microinstructions are transmitted directly from the microprogram memory to the central processor array. A 16-bit pipelined processor has a typical microcycle time of about 125 ns, while the simpler, non-pipelined design has a microcycle time of about 300 ns. The pipelined processor can execute about eight million microinstructions per second and the non-pipelined design, about three million microinstructions per second.

Many other system organizations, including multiprocessors, can be implemented. For example, many MCU-control memory sections can share one central processor (CP) array when many similar machines or devices must be controlled. Sharing a CP array will rarely affect control speed, since control data is processed at rates far higher than normal machine operating rates.

Since the Schottky LSI devices can execute millions of microinstructions per second, throughput is very high. Throughput is further enhanced by novel logic functions that minimize the number of microcycles required to execute a macroinstruction or other system command. These techniques also minimize the number of ROMs used in the microprogram memory, since fewer microinstructions are stored.

Several operations that normally require a sequence of microinstructions have been reduced to only a single microcycle. These include three operations performed very frequently by processors and controllers: maintaining the macroinstruction program counter; masking and bit testing; and multibit data shifts.

Testing a bit or bits in a register is often a condition for a microprogram jump. Conventional processors may destroy the data as a result of masking and testing for the desired conditions. But succeeding microinstructions may require use of the data. Thus, the processor must go through extra cycles to save and restore the data.

This additional delay is avoided by a new technique called conditional clocking. A bit in the microinstruction "freezes" the clock momentarily during the testing operation. The test result is sent to the MCU by the CP array, but the CP registers are not affected. This allows the CP array and MCU to perform a nondestructive test and a microprogram jump in one cycle. The original data remain in the CP array register for use by later program steps.

Multibit shifts simply require bus interconnections and a microinstruction that chooses the desired data paths, rather than repetitive bit-shifting operations.

Cost of the MCU and eight CPEs for a 16-bit computer is less than $200 in 100-up quantities. For system development work, a kit is offered, containing design information and all the LSI blocks and microprogram memory circuits needed to build a large, complex system. The kit costs $720.

For further information, contact Intel Corp., 3065 Bowers Ave., Santa Clara, Calif. 95051

Circle No. 40 on Reader Service Card