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articles

the cover

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spectral lines

Engineering and emotion

In the previous issue, we broached the topic of scientists and engineers expressing viewpoints concerning the application of technology to systems affecting the public. We endorsed a suggestion, made by Alvin Weinberg, that a greater responsibility in debates before the public would entail a clear distinction by a scientist (or engineer) between judgments based on scientific fact and those based on something less than fact. Such, however, may be an ideal that is not achievable.

There is some question as to whether it is even universally desirable. And, preferable or not, there is ample evidence that technical professionals, even when talking among themselves, often generously mix fact and feeling. In fact, as emotional temperatures rise, there is very little attempt made to distinguish between the two.

A few days ago, we observed a panel discussion in which the learned discussants debated—within the confines of the technical community—the question of whether traditional languages like Fortran and Basic will become even more firmly entrenched in our computer culture, or whether they ought to be jettisoned in favor of some more sophisticated and powerful language yet to be developed.

During the discussion a polarization took place that seemed to put the academicians in one camp (favoring avant-garde developments) and the industrial types in another (favoring refining and applying existing languages). The audience was not at all sure what it was observing in the sometimes heated exchange. Perhaps, some thought, it was a simple case of practitioners and academicians, with their respective vested interests, attempting communications at different "frequencies" and becoming frustrated in the process. Or it may have been at least a partial demonstration of how, when emotion enters the fray, less time and attention are given to the revelation of facts.

Upon witnessing such a discussion, the referee who perceives himself as objective is tempted to chide the participants for abandonment of their objectivity, and, clichéwise, to remind them that they seem to be generating more heat than light, their polarization is representative of two conflicting factors in a common problem (both are "right"; neither is "wrong"), or that they merely have a language barrier (e.g., all applications are "trivial" in the mathematical/scientific sense, while clearly not trivial to the practitioner).

Yet upon reflection, one has second thoughts. Perhaps polarization that occurs on occasions such as this is a mere ploy. Is it intentionally invoked to heighten the problem definition? To underscore a position? Such second thoughts give rise to the notion of "advocacy science." The suspicion is reinforced by a professor of computer science who tells that students of a particular language or programming strategy become such strong advocates of their "own" approach that they virtually, if not literally, ostracize colleagues who embrace another approach.

An interesting question is thus raised: Can "advocacy" science be a catalyst for progress? Or is it a contradiction in terms? What about advocacy engineering? (That seems a more legitimate concept, particularly in view of the often successful practice of seeking competitive engineering approaches to the solution of a well-defined problem.)

It would be naive to believe that the technological community could operate without the use of advocacy techniques. As technological issues emerge in the social and political arena, the use of advocacy becomes more widespread. Albert Teich of the State University of New York told the Annual Meeting of the AAAS that as practicing scientists and engineers have found themselves increasingly involved in the policy process, either as full- or part-time advisors or as advocates for one position or another, the use and misuse of scientific advice has become an issue in itself.

Teich's studies suggest at least the following questions: tions:

- □ How can experts involved in technical disputes avoid becoming increasingly polarized with time, and their claims more and more extreme?
- □ In such cases, and even more so when experts in one field endorse scientifically questionable positions in another field, how does one cope with the tendency of a jaded public to discount the ultimate importance of scientists' opinions?
- □ How can expert advisors be induced to reject the self-righteous tendency to consider their own views as objective and those of colleagues with whom they disagree as biased?

The root question may well be: "Can technologists harness emotion so that it becomes a useful tool in advocacy exercises?" After all, if emotion in the locker room can "turn ball games around," will emotion in the laboratories, conference rooms, and Congressional hearing rooms do less? Yet it is clear that emotion, even in the hands of a skilled attorney, can be a dangerous weapon. Wielded by a technologist, it may prove a weapon with a recoil—one that could cost him his credibility and the respect of his peers.

Donald Christiansen, Editor

How to evaluate microprocessor instruments

On the plus side: flexibility, reliability, interface standardization; but some inferior designs confuse the user

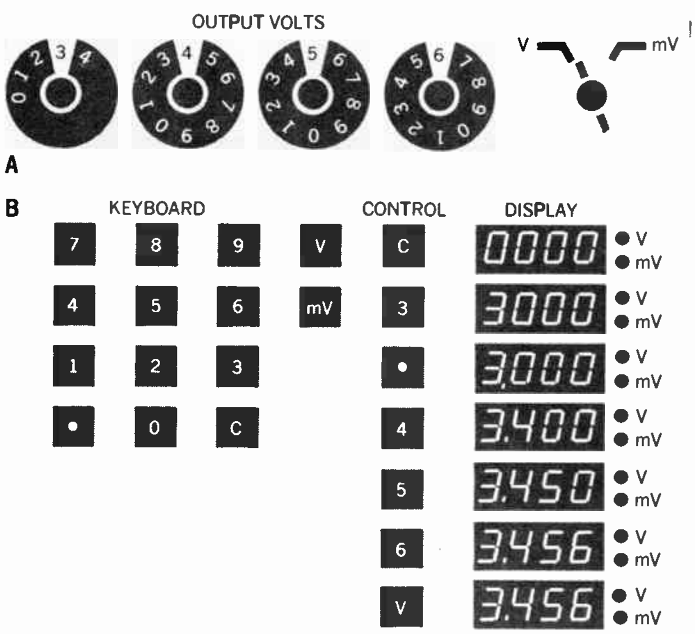
In a race to embrace microprocessor technology, the electronic test instrument industry has offered a variety of new instruments: oscilloscopes, voltmeters, counters, signal generators, data loggers, and more. But the instrument purchaser and/or user must see beyond the initial excitement and make down-to-earth decisions regarding the relative importance of the many features and advantages now claimed for these products. As a guide to the instrument user, examples of typical changes brought about by the use of microprocessors in instruments will be outlined here together with important points to be considered before purchasing a microprocessor-based instrument.

Displays and controls

Two elements of instruments that have been affected universally by the inclusion of a microprocessor are the front-panel display and the operator controls. One of the most obvious examples is the replacement of several rotary decade switches with a ten-key entry pad and numeric display. In a conventional design, the rotary switches serve as operator input devices, memory, and display of instrument status at any particular time. Both the switch detent and readout dial, as shown in Fig. 1, serve to inform the operator when he has changed the status of the instrument. In a microprocessor-based design, on the other hand, a ten-key momentary-contact push-button panel can serve in place of many rotary switches. A numeric display is necessary in order to provide "feedback" as the instrument is programmed sequentially with several decades of data.

Charles Newcombe John Fluke Mfg. Co., Inc.

[1] As shown in (A), dials provide "feedback" to the operator, display existing output settings, and even indicate the range of adjustment available. For example, switches are stopped at maximum and minimum settings. In a microprocessor-based instrument display, as shown in (B), each push of a button should cause a change in the display. Note that the entry sequence is not completed until either the "V" or "mV" display is illuminated. The display must provide some indication of overrange, e.g., with flashing digits.



For initial entry of data, the rotary switch and the push-button panel are about equal in convenience. When minor adjustments are to be made, however, the decade dial entry method is much more convenient. A simple one-step change of any decade switch in the classical instrument would require, in the microprocessor-based instrument, reentry of a multidigit number using push buttons. The push-button approach allows room for increased operator error and requires more time than resetting a decade dial.

A well-designed keyboard-oriented instrument probably should provide: (1) a convenient, straightforward method for incrementing and decrementing control data with easy selection of the decade to be controlled and with provision for "carry" and "borrow" if the decade range is exceeded; (2) an absolute minimum of different data-entry sequences; and (3) an easy assessment of the current status of the instrument by a quick glance at the information displayed on the panel.

Stored programs; unit conversion

Microprocessor-based instruments are beginning to appear that are user programmable in a similar manner to small dedicated-computer systems. These so-called "smart" instruments offer such features as the ability to learn and store several instrument setups for later recall by the operator. The operator who uses specific instrument functions on a repeat basis can save a lot of time with this feature.

The well-designed microprocessor-based instrument can contribute yet another benefit if the instrument manufacturer truly understands the ultimate application. For example, if typical operation of the instrument requires the operator to convert units (decibels to volts, millivolts to degrees Celsius, etc.) for every entry or readout, then time can be saved and operator errors reduced if these computations are provided within the instrument. Such computations may require a tradeoff in response time or maximum operating speed but, for most bench applications, when all operator functions are considered, there is a net gain in overall efficiency.

Microprocessor instruments in systems

When applying a microprocessor-based instrument to a computerized system, the most significant effect of the instrument on interface hardware will be caused by a definite move to byte-serial communications. This trend results from the instrument designer's desire to provide the least complicated and least expensive interface considering the bus-oriented nature of the instrument. Since typical system computers are also bus oriented, the situation is ideal. The principal problems will be in level translation and handshaking functions, but even some of these can be handled by software.

Since microprocessors are now available in 4-, 8-, 12-, and 16-bit configurations, it may be desirable to provide the facility in an interface for collecting data into 16-bit words for most efficient transfer to the computer bus. It is more likely, however, that this function will also be left to software manipulation with the computer.

Hardware interface standards are now emerging (e.g., IEEE Std 488, 583, 595, and 596.). The universal 16-bit duplex interface card offered by most computer manufacturers can be adapted easily to TTL-compatible, word-serial instrument interfaces requiring additional hardware only to satisfy certain handshake problems.

Instruments already on the market, whether they use 4-bit or 8-bit microprocessors, seem to be focusing on the 7-bit (plus parity) ASCII communications code for their interfaces. This opens the possibility for use of existing computer interfaces now used for a paper-tape reader/punch. These interfaces offer the additional advantage of existing driver/handler software, thereby simplifying the overall interface problem.

If the distance from the instrument to the computer is a problem and speed can be sacrificed, the approach may be taken to implement the bit-serial EIA RS-232 interface to transmit ASCII characters. At least one manufacturer now offers the three alternatives for serial interface just described.

Handling the software

Use of the ASCII code for instrument control is convenient and straightforward. The programmer can simply enter the appropriate character string and ask for it to be "printed" at the desired interface. No new intermediate code-converting software is necessary.

Some instrument manufacturers have not offered the most efficient command set possible in ASCII and the result is that a string of up to 40 characters may be required to define an instrument's operation completely.

When the instrument operation is purely binary in nature and speed is the dominant factor, it becomes desirable to abandon ASCII encoding and employ binary data formats. One byte of 8 bits can transmit data that would require three ASCII characters. It is likely that processor time on both ends of the transmission can be minimized as well.

It may only be a matter of time before instrument designs are being executed in binary with conversion to and from decimal (for convenience of the operator) being accomplished by the microprocessor. This situation will lead to an option for the programmer to communicate in binary or BCD.

The most exciting prospect for the programmer of tomorrow's instruments is the concept of distributed intelligence. It becomes possible to load a "program" from the system computer into the instrument memory and then have that program executed by the instrument microprocessor. Stimulus functions totally under control of the systems programmer can be loaded into a microprocessor-based instrument containing a D/A converter and the instrument commanded to generate the function without real-time dependence on the computer.

More isn't always better

In the rush to implement designs around the microprocessor, manufacturers may offer instruments that are so powerful, so flexible, and so general in design that they will be virtually useless. Such instruments will incorporate push buttons with several alternate functions depending upon the programming sequence. These push buttons could become very confusing and, if coupled with inadequate display feedback, can make operation of the complex instrument panel nearly impossible.

The instrument designer does a service to his customer by first understanding the final application of his design. By so doing, he knows how to incorporate features that represent a real convenience to the end user and can implement these features in a manner that makes instrument operation simple and straightforward. ◆

This article is based in part on a paper, "Microprocessor application tradeoffs in instrumentation," presented by the author at the IEEE 1975 Automatic Support Systems Conference.

Charles Newcombe is product planning manager for digital voltmeters with the John Fluke Mfg. Co., Inc. His career with Fluke includes engineering and marketing experience with computer-operated calibration systems and product management of calibration instrumentation. Prior to joining Fluke in 1966, he worked in metrology engineering for Lockheed in Sunnyvale, Calif. Mr. Newcomb is a member of the Precision Measurements Association.

The ubiquitous microprocessor

There is no denying the tremendous impact that microprocessors are having on instrument design and application. For this reason, we have devoted three articles in this special issue on instrumentation to microprocessor-based instruments. The accompanying article gives the potential user of a microprocessor instrument guidance on advantages and pitfalls. The second article gives examples of what is, and will be, accomplished with microprocessors incorporated into medical instruments. The third article addresses, with specific examples, the advantages of using systems and/or industrial controls and process instruments based on microprocessors. In addition, other articles in this issue discuss microprocessors in instruments to varying degrees.

Ronald K. Jurgen, Issue Editor

Software (and hardware) for the 'medics'

Medical instrumentation engineers have great expectations for the application of microprocessors in the hostile hospital environment

A normally enthusiastic biomedical engineer on the staff of a large hospital observed recently that he could probably contribute more to the quality of health care in that institution by improving its elevator service than he could by designing and applying new medical instruments. His statement may have contained more truth than humor. Constraints on medical instruments in a hospital environment can be so severe that any advance in technology may have little chance of getting into the health care system, let alone improve it. But in spite of hostile environments, lack of funds, shortages of skilled personnel, and myriad other problems, biomedical engineers are excited by the potential and the promise of the microprocessor. They know it will make new measurements possible and new systems practical that were not practical before.

Enthusiasm for the use of microprocessors in medical instruments centers on their power and flexibility. The ability to perform logical decisions and computations quickly and cheaply, coupled with the ability to use software programs—instead of hardwired circuits—to handle specific functions, has opened up a new era in medical instrumentation. There are already on the market new microprocessor-based medical instruments. Others are under development by medical instrument manufacturers and by biomedical engineers in hospitals and other institutions. And a possibly significant trend is turnkey systems, an approach to medical instruments that may not have been practical, or even possible, without the microprocessor.

Slow start; fast finish

Designing medical instruments with microprocessors makes a lot of indoctrination, particularly with software, and hands-on experience. But, as the following case history shows, the necessary efforts required to break away from conventional design philosophy can bring dramatic results.

A company in the Boston area was designing a new clinical laboratory instrument for testing blood samples. The engineers decided to develop two prototypes: one with conventional analog and digital electronics, the other with a basic 4-bit microprocessor. The conventional design was completed and running first. The microprocessor design got bogged down in such initial difficulties as setting up a developmental system and learning how to use it. At that stage of development, the conventional design appeared simpler and superior in performance.

When field trials of the prototype indicated a need for changes in the measurement procedures and algorithms, the microprocessor prototype came into its own. The microprocessor design, just barely completed, was quickly modified and reprogrammed, and began functioning properly. As the result of further field trials, alarm algorithms were added to the instrument to warn of inconsistencies in results. A capability for sending messages to the operator to reduce the probability of human error in handling blood samples was incorporated. Self-check and self-calibration features were added. All of these additional features would have been formidable design problems in the conventional prototype but were incorporated quickly into the microprocessor version. And, during prototype development, microprocessor costs decreased appreciably, giving the microprocessor design economic advantages over the conventional design.

Ronald K. Jurgen Managing Editor

A microprocessor instrumentation center

Under a grant from the National Institute of General Medical Sciences, the Harvard–M.I.T. Program in Health Sciences and Technology has established a Biomedical Engineering Center for Clinical Instrumentation. The new Center involves interdisciplinary collaboration of engineers and physicians in the research and development of new medical instruments based on microprocessors. Research, evaluation, and testing of the clinical instruments will be performed by collaborative groups from the Massachusetts Institute of Technology and from Beth Israel Hospital and Peter Bent Brigham Hospital—teaching hospitals of Harvard Medical School. The Center has four initial projects underway.

The initial project nearest completion is a portable system for real-time analysis of cardiac arrhythmia (irregular heartbeat). Intermittent cardiac arrhythmias are an important health problem but it is difficult to identify an arrhythmia and patients respond to therapy in different ways.

Portable ECG tape recording systems have demonstrated the feasibility of data collection while patients are moving about. Microprocessors carry the process one step further by being the basis for a real-time arrhythmia analyzer that is small enough to be portable. It will permit increased speed of access to the data by the physician and increased efficiency and safety of the therapeutic trials. It will also make possible interaction between the instrument and the patient. For example, the device not only will act as a passive absorber of patient ECG data and verbal inputs volunteered by the patient, but it will also actively request responses from the patient based on an ECG analysis. It may even remind patients to take medication, suggest changes in physical activity, request descriptions of behavior, request that the patient call a central point to "dump" processed data, etc.

A simplified block diagram of the portable arrhythmia analysis system is shown in Fig. 1. It will be contained in a package measuring 5 by 13 by 20 cm with a weight of about 1.3 kg. The processor will be able to communicate with a central data collection point via the telephone (through use of a modem). A real-time analog ECG tape recorder will be worn simultaneously by subjects during the evaluation process since comparisons must be made between the real-time data analysis and off-line, closely controlled analysis of the input data by human observers. The tape will include a second channel for time and special-event marking. The initial data reduction stage of the system has already been implemented on an Intel 8080 microprocessor.

The goal of the second project at the Center is the development and evaluation of a clinical test battery for patients complaining of dizziness or disequilibrium. One part of the project will be an evaluation system in which horizontal and vertical eye movement responses are analyzed by a microprocessor under a logical branching test sequence. The patients will be stimulated with several of the following tests in a single physical system, according to a logical branching program: horizontal rotation; vertical oscillation; eye deviation; head tilt; caloric, galvanic, and optokinetic stimuli; and voluntary movements.

The second part is a movable posture platform. The standing patient will be monitored for normal standing and for recovery from an imposed postural disturbance under conditions designed to test visual, motor, and other contributions to disequilibrium. Parameters of body sway, torque, and electromyograms are calculated with one microprocessor while another controls the tests.

The third instrumentation system under development, a pulmonary function tester, will be clinically useful for the detection and/or assessment of lung disorders. It will incorporate a whole-body plethysmograph and a respiratory gas analysis system incorporating dedicated microprocessors to undertake operational control of the equipment, to communicate with the user to allow him to select which waveform he wishes to collect and process, to digitize the signals selected, to perform the indicated calculations, to communicate with subunits so that digital information that is common or necessary for final computation of tests can be transferred, and to output the final data. The system is expected to provide more information about lung function more quickly than other systems presently available and in a stand-alone mode.

The fourth instrument, a thermal diffusion probe for continuous monitoring of tissue perfusion (the forcing of blood through tissue), will be a microprocessor-based system useful for expanding the clinical applicability of the thermal diffusion probe as a continuous, minimally traumatic, portable tissue perfusion monitor. The tissue-probe system will be modeled analytically to include a tissue blood flow term, which, after appropriate processing, will be read on line as blood flow in cc/min/100 cc tissue.

Planned for future implementation at the Center is an inventory of commonly anticipated function modules such as A/D converters, scope displays, mass-storage devices, and microprocessors. Once a basic matrix is developed around which instruments can be built, then designing a new instrument will merely mean going to the inventory for the standard modules, selecting some input/output devices, and developing a programming system to allow efficient use of the hardware. By this technique, it will be possible to produce a new instrument in a few weeks at low cost. It will no longer be necessary to design a new instrument from the ground up each time one is needed.

The Center has also developed its own compiler, called STOIC (stack-oriented interactive compiler). STOIC uses a higher-level language developed at M.I.T. and incorporates a built-in assembler. The built-in assembler tends to compensate for the inherent slowness of microprocessors and makes it possible to get the ultimate in speed from them. The compiler is said to be efficient in terms of a programmer's time and is also core-efficient because of its fundamental architecture.

Anesthesia delivery system

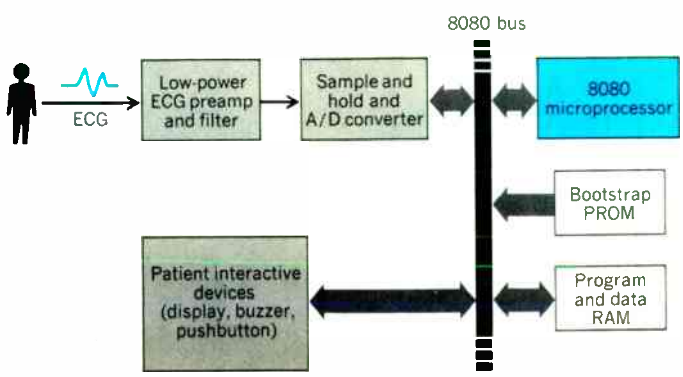
At Massachusetts General Hospital in Boston, where anesthesia was first demonstrated in 1846 by William Morton, work is underway on development of a microprocessor-based anesthesia delivery system. It is expected that the microprocessor system will be able to eliminate, or at least minimize, some of the potential safety hazards of existing equipment—hazards that result from human error in such functions as reading flowmeters and operating controls.

The new system will provide the same basic functions as does existing equipment. It will supply oxygen, anesthetic gases, and volatile anesthetic liquids in controlled flows and concentrations, and will provide a means for controlled ventilation of the patient. It will include a supply of compressed gases and provisions for direct connection to low-pressure (50-psi) central gas supplies.

Existing delivery systems have mechanical major subsystems for control and display of gas flows and anesthetic concentrations that cannot communicate with any other part of the system. There are also severe limitations on how information can be presented and how the console and workspace can be organized. Every new alarm or fail-safe feature requires a new gadget with its own power supply and enclosure. By using an electronic system with a microprocessor, safety can be improved and new ideas and new technologies can be incorporated as they become available without creating more confusion and clutter.

The microprocessor anesthesia delivery system's

[1] Simplified block diagram of a portable microprocessor-based system for real-time arrhythmia analysis.



block diagram is shown in Fig. 2. Oxygen and nitrous oxide are proportioned by two digital control valves. Each valve contains eight orifices that are opened or closed by solenoids. Their cross-sectional flow areas are weighted in a binary fashion. The first has a flow of 39 ml/min at 50-psi input pressure, the second has 78 ml/min, and so on, up to 5.0 ml/min for the eighth and largest orifice. Since there are 8 binary bits, there are 256 combinations of open and closed orifices with a resolution of 39 ml/min, the smallest bit. Each orifice is a constant-flow source because a sonic nozzle is used as the restriction (flow then is a function only of up-stream pressure).

An electronic injection system is used for metering and atomizing the liquid volatile anesthetics. It is based on automotive fuel injection schemes and uses a modified Bosch automotive fuel injector.

The valves, injectors, displays, alarms, and peripheral functions are controlled by an Intel 8080 microprocessor. The microprocessor as the central processing unit, together with time bases and memory, forms a microcomputer. It receives analog inputs including regulated oxygen and nitrous oxide line pressures and inspired oxygen concentration. It is also given set points through controls on the machine console. The microcomputer computes the required effector settings through software algorithms and constants stored in the PROM and then acts to set the digital value positions and injector frequency. The computer also initiates and maintains a variety of displays through which the operator can monitor the system function. Through software and the console displays, the microcomputer warns the operator of malfunctions in its own system or of unsafe actions on his part.

The microprocessor-based approach to anesthesia delivery is said to have the following advantages: Because of consolidated information displays and controls, the microprocessor system permits strict adherence to human factors principles to help minimize the incidence of human error. Meaningful controls and displays and special functions simplify the task of the anesthetist. The system provides an easy means for implementing modifications as testing and evaluation proceed. Rather than redesigning hardware, effector algorithms can be changed, displays can be modified, and fail-safe and self-checking features can be added through software. The system is easily expandable and can be improved readily as new technologies arise.

Tracing methadone's behavior

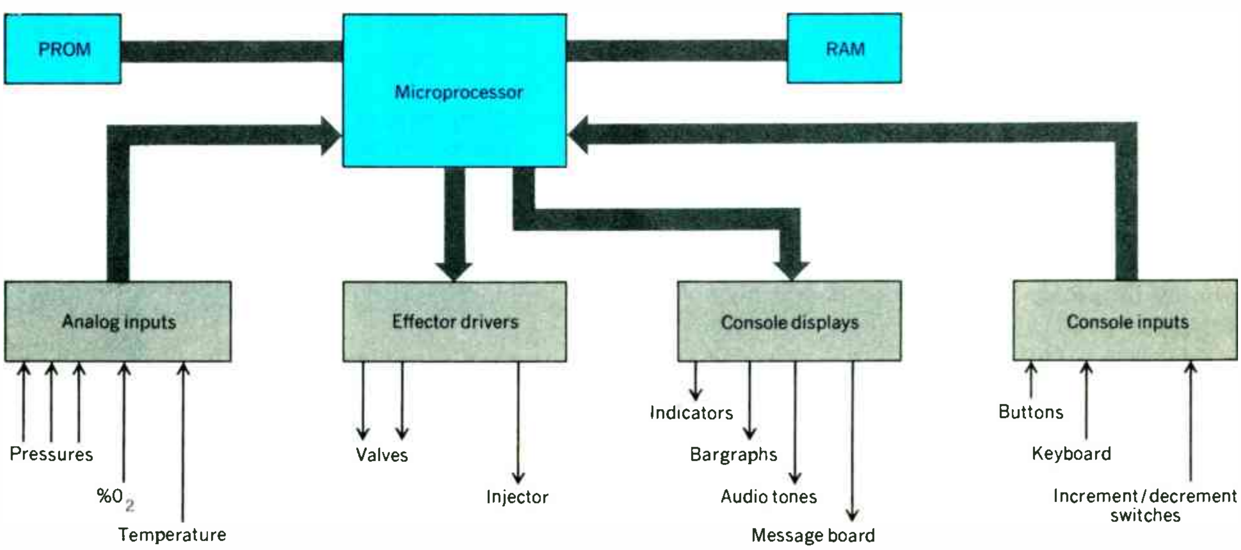
Tracing the behavior of methadone, a heroin substitute used to help addicts kick the habit, in the human body is a difficult task. Scientists at Argonne National Laboratory have been experimenting with stable isotopes that can be used to "tag" methadone and other substances which researchers want to locate in the human body. The problem is that measuring stable isotope concentrations in samples of blood or tissue is extremely difficult. Until recently, the only way to compute the ratio of heavy to normal isotopes in a sample had been to run a mass of data through a large, expensive computer. But now, an instrument has been developed for monitoring ions containing a stable isotope and for computing stable isotope ratios. Called a spectral analysis microprocessor, it is being manufactured by Scientific Research Instruments Corporation, a subsidiary of G. D. Searle and Company, based on a design developed at Argonne.

The spectral analysis microprocessor drives a gas chromatograph/mass spectrometer, an instrument that separates individual components out of a mixture according to their mass. It identifies up to eight ions separated from a sample in a single gas chromatographic run, automatically subtracts background ion intensity, and prints out raw data or ratios along with time parameters as soon as the sample has been analyzed. The instrument requires only four push-button steps: punching in the ion peaks to be monitored, determining background ion intensity, introducing the sample and determining the ratio of ion densities, and printing out the data on a six-digit line printer.

Argonne scientists predict that the new microprocessor instrument will cut the time and expense involved in using computers to obtain isotope ratios and will also facilitate the use of stable isotope tracers as diagnostic tools.

Commercial production of the new instrument is part of an ERDA program to transfer new technologi-

[2] System block diagram for a microprocessor-based anesthesia delivery system. The microprocessor approach permits selection from any of a variety of display techniques.



cal products and processes from its multiprogram national laboratories to industry.

Beta- and gamma-ray counters

At Packard Instrument Company, Inc., a subsidiary of Ambac Industries, Inc., microprocessors have been incorporated as the controlling units for automatic liquid scintillation counters, which measure beta radiation of a radioactive sample dissolved in a suitable solvent; for automatic gamma-ray counters, which measure gamma radiation of a radioactive sample; and for sample preparation units, which aspirate a known amount of different reagents and patient serum and dispense them into a test tube for many clinical and research applications. The main medical applications are radioimmunoassay and related procedures for the measurement of hormones, vitamins, drugs, and other classes of substances in biological fluids in vitro.

The advantages in using the microprocessor in place of conventional logic, according to Packard, are: It is cheaper (the microprocessor replaces about 100 to 200 ICs), more reliable, and easier to service; it enables putting more data reduction in the instruments without using any external computers; and it permits the design of instruments with easier operating procedures.

Respiratory measurements system

In the treatment of respiratory diseases, it is often important to be able to measure gas flow during a patient's inhalation and exhalation as a function of time and compare them with comparable measurements for normal persons of the same age, sex, and weight. Minicomputer systems have been available but have been limited in application because of their expense.

Puritan-Bennett Corporation, Kansas City, Mo., is marketing an Intel-microprocessor-based respiratory measurements and comparisons system called REMAC. It sells for less than $6000 and measures and calculates five different respiratory variables in each of two different operating modes. Patient data are entered on a pull-out data-entry keyboard and the measured variables can be read out sequentially from a digital display or on an accessory printer.

[3] The entire general-purpose, biomedical computer system developed at the VA Hospital in San Diego, Calif., fits into the plug-in module of a strip-chart recorder.

Biomedical computer system

At the Veterans Administration Hospital in San Diego, Calif., a biomedical computer system costing less than $3000, based on the Intel 8080 8-bit microprocessor, is in clinical use. It is housed in a single-channel Hewlett-Packard strip-chart module, Fig. 3, containing all of the computer functions as well as a high-efficiency power supply. The computer functions are contained on up to eight printed circuit boards interconnected by high-reliability gold–gold stacking connectors and a front panel board for physician communication. The unit receives analog signals directly from patients and/or external equipment, processes these data digitally, and then outputs results to the strip chart by conventional analog output, alphanumeric dot matrix, or voiceprint-like density modulation particularly suited for spectral analysis.

The biomedical computer system is intended for development into turnkey systems where the user need only turn on the power and hook up the patient and the computer does the rest. To accomplish this objective, the hardware includes provisions for checking itself as to correct operation, checking lead impedance (input leads have high impedance to chassis ground as one of several patient-protecting schemes incorporated in the system), adjusting gain to keep signals within range, notifying medical personnel in case of emergencies, self-calibration, and direct physician interfacing with both input and output.

For any potential user of the biomedical computer system who does not wish to develop his own software, system packages are planned to perform certain functions. The result will be true turnkey devices used for evaluation, data gathering, and final use. Potential uses range from complex pattern generation to simple artifact removal. Some possible uses include signal processing (EEG, EKG, heart sounds), signal combining and calculation (systolic time intervals, cardiac output, respiratory variables), monitoring and warning, display methods, control, trends, rapid system development, testing, debugging, and redesign.

If the testing of various monitoring systems is required at multiple locations, the software only needs to be written once, since each unit will be a standard unit with identical memory. Since analog I/O is available, no special interfacing is needed for the computer to start processing data from tapes, animals, or humans. With the biomedical computer, there is no need to build hardware to test an idea and then rebuild it to incorporate improvements—all can be done with easily changeable software. ◆

Consultants for this article were: Stephen K. Burns and John Sachs of M.I.T.; Ronald S. Newbower, Jeffrey B. Cooper, and Edwin D. Trautman of Massachusetts General Hospital; Peter Cheung of Packard Instrument Company, Inc.; Richard E. Pikul of Puritan-Bennett Corporation; and Robert Fleming and N. Ty Smith of the Veterans Administration Hospital in San Diego.

The microprocessor takeover

On-the-spot mathematics, automatic testing, and portable calibration are yielding to microprocessor solutions

Microprocessors are increasing the thoroughness, accuracy, flexibility, speed, power, and—not least of all—the economy of instrumentation and control systems. These increased capabilities are opening up applications ranging from satellite hardware testing to ship-stress and water-pollution monitoring.

Diagnostic test patterns and routines, generated in a flexible and accurate manner by microprocessor systems (microcomputers), are being used to monitor the operation of circuits and equipment. The microcomputers recognize errors and identify faulty hardware.

Automatic calibration and recalibration, made possible by microcomputers, are speeding production testing and instrument maintainance, making self-contained, economical electronic systems available for applications that formerly required prolonged attention from skilled technicians.

Calculated results, obtained by microcomputers and displayed in formats best-suited for human interpretation, are extending the effectiveness of human decisions. High-speed computation, too, is being made more accessible as microcomputers interface to fast, hardwired arithmetic and to larger computers.

The impact of these and similar developments on instrumentation and control systems is just beginning to be felt. This article samples the information *Spectrum*'s editors have gathered in recent months about such applications (Table I, p. 48). The examples given are not necessarily the most sophisticated current uses of microprocessors in instrumentation systems, but they should convey a sense of the new design possibilities opened up by microcomputer techniques.

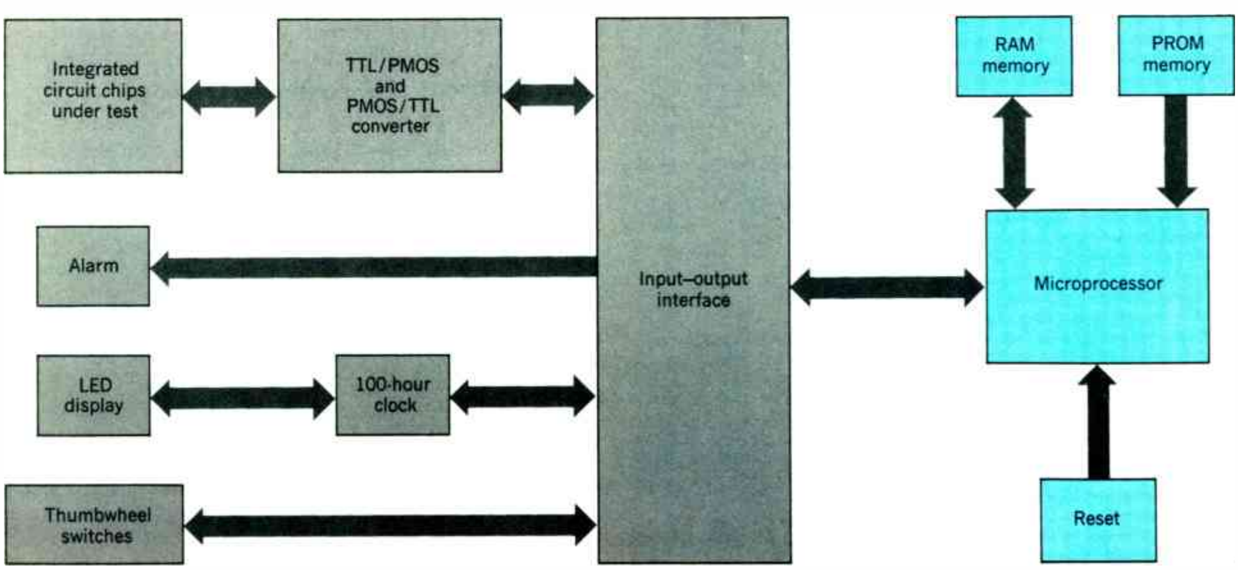
Howard Falk Managing Editor
Gadi Kaplan Associate Editor

Elegant production testing

Microprocessors are making more-powerful production testing methods feasible, and these seem particularly effective where complex measurements are to be made. For example, at the Goddard Space Flight Center, PMOS-LSI chips formerly were checked manually during burn-in. Inputs such as spikes and pulse trains were used, and output waveforms were displayed on an oscilloscope. Now a microprocessor system (developed by Information Development and Applications, Beltsville, Md.) automatically exercises and monitors the LSI chips during burn-in (Fig. 1). Parallel bit-patterns are generated by the system. The patterns are stored and are selectable, for different chips, by means of thumbwheel switches. Bit outputs from the chips are monitored, and any detected error stops the test clock, which is set to complete the test after 100 hours of operation. The malfunctioning chip is then manually removed, and the clock and the system are restarted to continue the test.

Software to handle the test procedures, and to gen-

[1] Burn-in test for integrated circuit chips. Digital signals to and from the PMOS chips under test pass through a voltage-level-shifting converter to microcomputer TTL circuits. Thumbwheel switches allow various test signal sequences, stored in PROM memory, to be selected. Stored-program routines determine when various sequences and tests are used. Times of failures, if any occur, are shown on the LED display. The system then alarms and halts.



erate special test patterns for more than ten different types of LSI chips, is stored in 2K-bits of PROM memory. One 256×4-bit RAM handles the thumbwheel switch data. One of the problems that had to be solved during the design of this system was to interface the TTL logic circuits of the microcomputer with the PMOS chips under test. TTL logic levels had to be pulled up to meet the PMOS levels, and vice versa.

The overall result for the operations at Goddard has been more meaningful testing. No longer does there have to be constant human monitoring of chip burn-in, the exercise routines are more thorough, and the measured times-to-failure are more accurate.

Microprocessor-based test systems can provide tremendous flexibility combined with automated testing speed and accuracy. Consider the test problem a microprocessor solved at General Dynamics/Electronics in San Diego where complex relay switching networks are now used in conjunction with a hybrid computing system. The mercury-wetted relays are mounted on large circuit boards and are very difficult to test by hand. Using a microprocessor-based system, the relay boards are now checked by diagnostic programs controlled from a teletype keyboard.

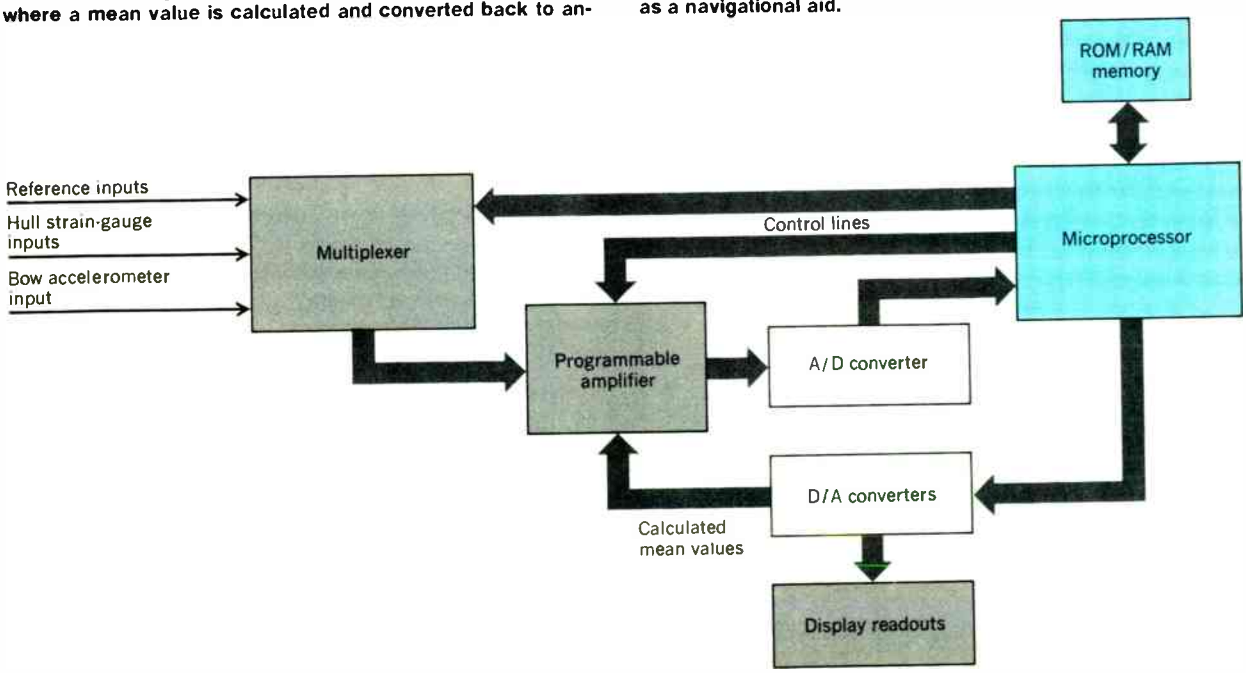
Although hardwired test logic, specifically designed for a single task, may operate at higher raw speeds than a microprocessor system, the flexibility of the microprocessor can still allow it to do more effective work. For example, a large computer manufacturer had been checking disk-memory operation and disk surface condition, using hardwired logic to control and test one disk pack at a time. When a microprocessor-based test system was installed, three disk drives could be economically tested, on a time-shared basis.

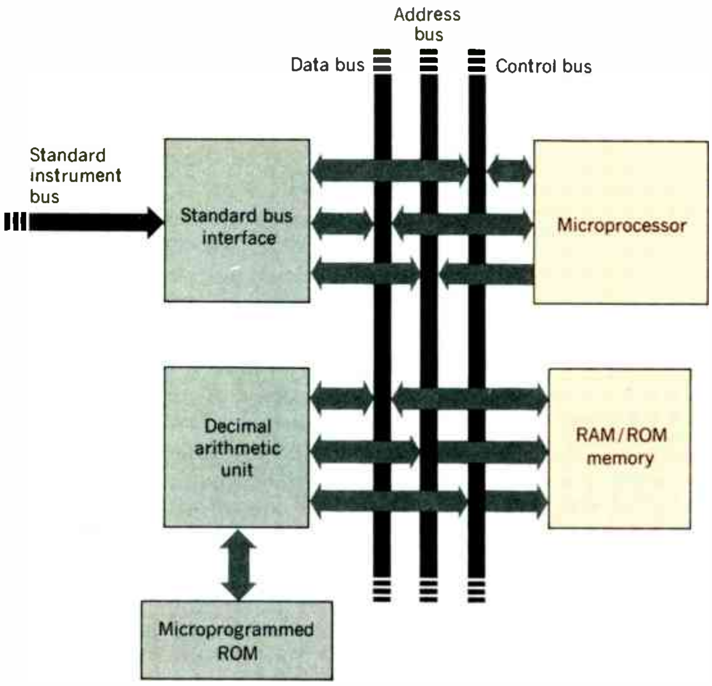
The relentless eye of a microprocessor-based system is now being used by a large plywood manufacturer to scan lumber sheets for knotholes and other defects. Before this system was introduced, a human operator would continuously scan the sheets for defects. Because of the relatively fast speed of the lumber sheets in passing the operator (about 60 m/min), and due to normal human fatigue, errors would be introduced, good sheets rejected, and bad ones accepted. Now the inspection is more reliable and accurate.

Like electronic measurement, mechanical production testing can become quite complex. One complicated machine-adjustment procedure used to be performed by hand by a customer of Moxon, Inc., in Irvine, Calif., using depth micrometers. The procedure took a skilled operator three days to complete. Now, the same job is done in 15 minutes, using a microprocessor-based system. Linear variable differential transformers (LVDTs) are mounted to gauging fronts to form the sensors for this system. Without the microprocessor this arrangement would be very difficult to use. Normally, each LVDT transducer would have to be adjusted mechanically with extreme accuracy to achieve an electric null for the test fixture, since a mechanical misalignment as small as 5 μinches can produce a noticeable plus or minus output voltage. To overcome this problem, the microprocessor in the Moxon system reads and stores each actual transducer output reading, calculates the offset required for electrical null, and stores this value in memory. Each time the system is polled for an actual adjustment value, the transducer output is combined with the offset value and the result is displayed for the operator. This automatic feature assures that all readings are from a zero base line.

For the machine-adjustment procedure, the operator has a master jig, on which he mounts a carrier with 20 transducers, each connected to the microprocessor. When he presses a "calibrate" button, the microcomputer picks up and stores the readings of each of the

[2] Hull-load monitor. Strain gauges mounted on a ship's hull, and an accelerometer that tracks vertical acceleration of the ship's bow, feed analog signals into this system. These are converted to digital form and fed to the microprocessor where a mean value is calculated and converted back to analog form. In the programmable amplifier, this mean value is subtracted from incoming sample values to allow accurate computation of statistical standard deviations. As these deviations are calculated by the processor, they are displayed as a navigational aid.





[3] Decimal mathematics for instruments. The decimal arithmetic unit in this system is designed to perform fast computations on instrument data, including use of ROM-stored microprograms for sine, cosine, and other transcendental functions. These operations are controlled by the microprocessor, which also manages the control and logging of instruments attached to a standard (IEEE Std 488-1975) bus.

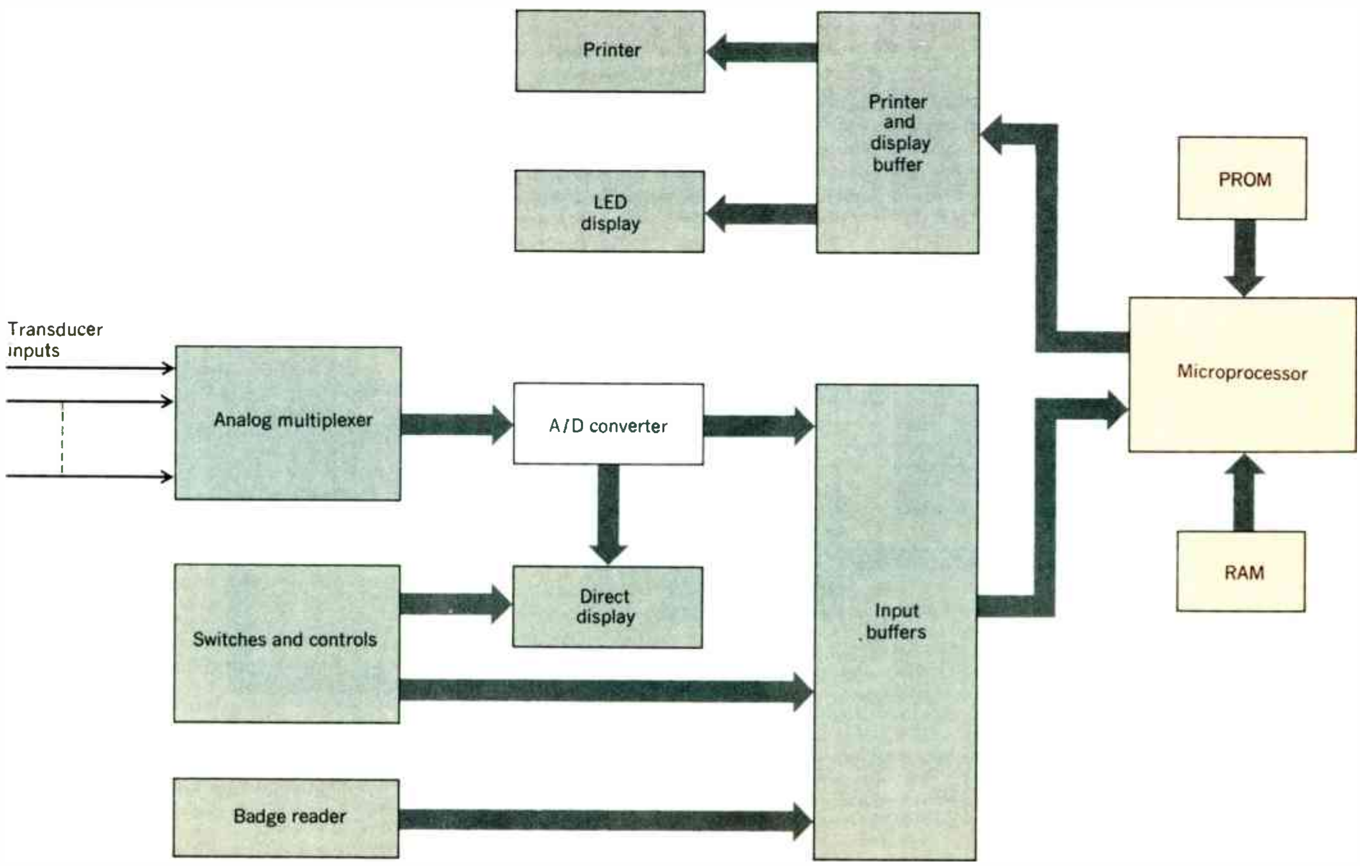
transducers; these are the desired readings for a correctly adjusted unit. The operator then removes the transducer carrier and places it in position on the unit to be calibrated. Watching linear light-emitting diode arrays, he adjusts the unit so that the measured points fall within specified tolerances. A digital display is available for those situations where more accurate readings are needed. Red-green lights on the microcomputer system panel provide go/no-go indication that each measured point is, or is not, within tolerance. When this procedure has been completed for all 20 transducers, the printer records the actual transducer readings (to a resolution of 100 μinches), along with the date, time, and serial number of the unit being adjusted.

Unlike the many gauging systems that provide scaling adjustments and zero adjustments, but whose results must be compensated by offset factors obtained from outside the system, this system recalibrates itself both in terms of position and sensitivity. Furthermore, it is flexible. The user can alter a UV erasable PROM to accommodate different parameters and units. For each different gauging job, a PROM is plugged into the front panel of the microcomputer system.

Other production test and control problems now being solved by microprocessor-based systems include:

- Temperature measurement in the steel industry, with systems that carry out time/temperature calculations
- Multiloop process control by systems like the eight-

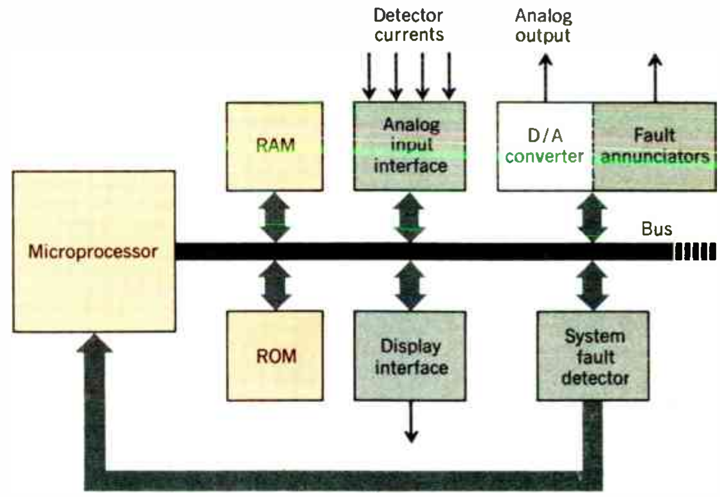
Gauging control and logging. Here, inputs from gauging transducers are multiplexed, converted to digital form, and fed to a microprocessor. A PROM memory provides preestablished tolerance parameters for the measurements. Push buttons and thumbwheel switches control printing, calibration, and time-date information. Displays are provided for monitoring individual transducer adjustments. The operator watches the display—usually a lighted-bar arrangement, with bar-increments on each side of center representing deviations from null—and adjusts the transducer until a null reading is obtained. A printer provides a permanent record of transducer readings.



loop controller recently developed at Honeywell Inc. in Fort Washington, Pa.

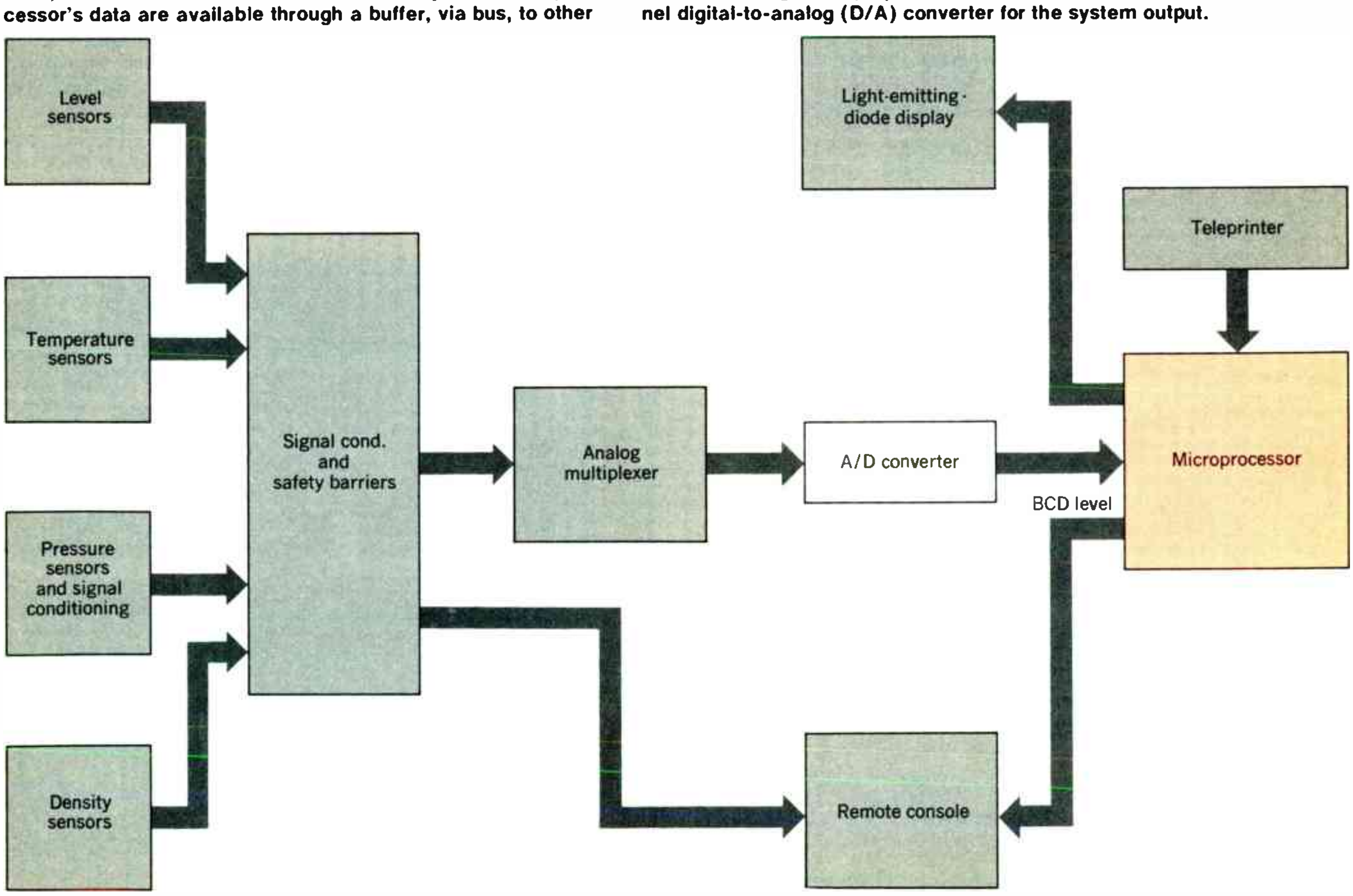
Mathematics on-the-spot

Microprocessors are certainly not noted for their ability to handle high-speed or massive mathematical calculations, but the fact that they can perform relatively simple mathematical computations seems to be the key to a number of applications in instrumentation systems. For example, the ability to perform computations that produce system readouts in readily useful form can be critical to the success of an instrumentation system. In a ship's hull-load monitoring system, developed at Detnorske Veritas in Oslo, Norway, by Paul Fredriksen and his colleagues, the key readouts are statistical, standard deviations of strain gauge and accelerometer readings. These standard deviations have been shown to be proportional to the dynamic loads experienced by the hull when the ship is underway, so the readouts help the navigator decide whether his ship might be damaged by strains due to its speed and course. In the Norwegian system, a microprocessor computes the necessary mean values, squares, and square roots to obtain the standard deviations. The processor also controls readings from transducers mounted on the ship's hull, and operates alarms when sensor signals drift outside their normal range, or when there is a malfunction of the monitoring system (Fig. 2). The hull-surveillance system has been installed in



This microprocessor-controlled liquid-level measurement and monitoring system, designed by Simmonds Precision Products, Vargennes, Vt., and called Custody Transfer Measurement system, is intended to display and record, for billing purposes, liquefied natural gas levels in modern cryogenic gas carriers (ships). The various sensors are connected, via safety circuitry (which limits the amount of energy that can be transmitted into the liquid gas—a potentially hazardous area), to signal conditioners that generate desired voltage levels. These voltages are multiplexed, digitized through the analog-to-digital (A/D) converter, and processed by the microprocessor for local and remote display as well as for printout. Additional elements in the system are program and data memories, as well as self-test and failure detection features.

In this microprocessor-based system designed at Westinghouse, Pittsburgh, Pa., for continuous monitoring of the axial power distribution of a nuclear reactor's core, the microprocessor card contains, in addition to the microprocessor itself, a clock and automatic restart circuitry. The microprocessor's data are available through a buffer, via bus, to other interfaces. These are: random access memory (RAM) and read-only memory (ROM) for program storage; four-channel, multiplexed analog-to-digital (A/D) converter for input currents from four neutron-sensitive detectors positioned around the reactor; digital displays, annunciators, and a single-channel digital-to-analog (D/A) converter for the system output.



I. Examples of existing or shortly expected applications of microprocessors in control, instrumentation, and data acquisition and processing in industrial and related environments

Area or Industry	Applications
Agriculture	Cotton gin efficiency monitoring system
Avionics	Avionics "black boxes"
Buildings (large)	Remote control of air conditioning and ventilation and lighting; energy management systems for demand limiting and load shedding; fire and smoke remote alarm systems; security systems (data acquisition, logging, and management); preprocessing of telephone line data in real time for monitoring commercial premises against burglaries
Chemical	Control of processes in chemical plants (a special case—multiloop process controllers), control of cathode-ray tube operator display system for process control; gas and liquid analysis
Food	System for batch mixing of dry pet foods; instrumentation and computing system in a sugar refinery
Garment	Control of cloth cutters
Lumber	Control of lumber-handling machinery
Manufacturing (general)	"Smart" terminals for programming programmable controllers, control of readouts and displays (cathode-ray tube, for example); use in numerical machine controllers; computer interface
Marine	Shipboard custody transfer systems
Material handling	Crane controllers
Metal	Control of acoustic-emission monitoring of welds
Motor vehicle	Automatic welding facility for truck cabs
Packaging (general)	Control of wrapping machines
Paper	Supervisory control, data acquisition
Plastics	Gauging of plastic sheets; control of line and extruder speeds; control of gauge position
Traffic control	Vehicle control for isolated intersections
Utilities	Energy management and control; demand controllers; remote control of power generating substations; continuous monitoring of axial power distribution in nuclear reactor cores
Other	Control of computer output devices such as plotters; industrial manipulators programmable by teaching

A time to digitize

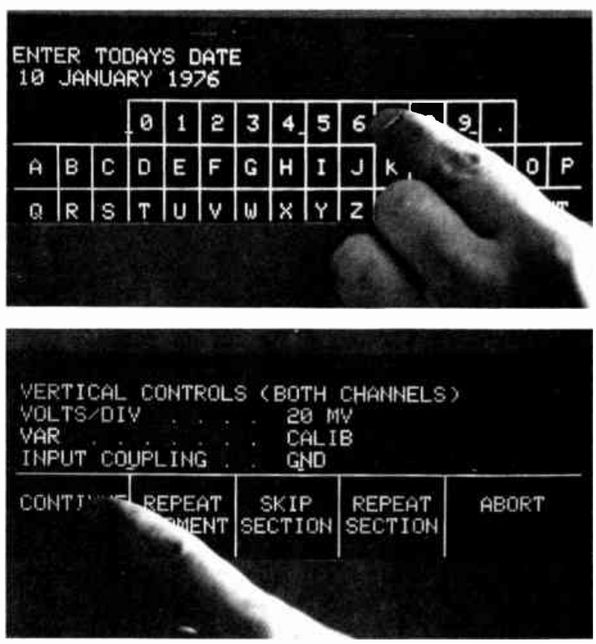
In some specialized instrumentation applications, where analog circuitry has been developed over the years to do a specific task, the microprocessor is still unable to compete economically. A case in point is a measuring system manufactured by Leeds and Northrup, North Wales, Pa., where analog circuitry is used to linearize the output characteristic. L&N is still waiting for the cost of microprocessor systems to fall below that of the passive and linear active components presently incorporated in that design. However, elsewhere in the same company, microprocessors are being viewed as ideal replacements to analog circuitry. A case in point is in equipment that requires square root computations (the square root of pressure is required for process flow calculations). Here microprocessors are successfully replacing analog circuitry.

several ships, and users have found it a valuable aid to ship operation.

Sometimes the key to a microprocessor application may be the ability to get more accurate results than can be obtained by other methods at similar costs. In a water-pollution monitoring system, developed at Oak Ridge National Laboratory, an accuracy of 0.1 percent in readouts of water flow was required. The designer, Michael J. Roberts, has used a microprocessor-based system to achieve the required nonlinear conversions and integration with specified precision. The flow signals being measured have a wide dynamic range—greater than a hundred to one—more easily accommodated by digital than by analog computation.

The aim of the system is to assure that a measured analytic sample is taken each time precisely 1000 cubic feet of water flow past. This flow is obtained from calculations involving the water height measured by a float inside a stilling well near a dam. The float is connected to a pulley whose shaft moves a potentiometer to create an analog voltage proportional to the height of water in the well. The relationship between this height and the flow of water over the dam's weir is known, and is stored in tabular form. The microprocessor samples the analog height-voltage, and converts this reading to flow by table lookup and interpolation.

Versatile plasma display and touch panel for microprocessor-based calibration system. Four types of display-response modes are used in the calibration system developed at the U.S. Navy Metrology Engineering Center in Pomona, Calif. In the *alphanumeric mode*, a keyboard of letters and numbers is displayed, and the operator "touches" in the desired text. As seen below, ENTER TODAYS DATE is the system instruction; the second line is the text touched-in by the operator. *Space*, *back-space*, and *enter* commands are also displayed. In the *instruction mode* four lines of instruction can be displayed—shown below are instructions for oscilloscope setup—and the operator can touch-in any of five commands. The "sections" referred to are calibration steps involving vertical deflection, sweep, etc. In the *operator evaluation mode*, not shown here, the operator reads four lines of text, and touches-in a *pass* or *fail* command. Finally, in the *measurement/stimulus mode*, also not shown here, the operator adjusts parameters such as vertical deflection amplitude using *up* and *down* touch-in commands.



Flow is then integrated numerically by simple summation.

Microprocessor computations can often be usefully teamed with those of larger computers. For example, in some systems where instruments are connected to a computer for analysis of their output data, the load on that computer can be considerably reduced if the instrument output is preprocessed and condensed. At the Upjohn Co. in Kalamazoo, Mich., a medium-sized computer interfaces with a number of different analytical instruments to process the instrument data. A microcomputer is now being used to format data from scintillation counter channels. In the past, these channels, carrying teletype-format data, were fed to the computer in parallel. Now, with the microcomputer, the channel data are reformatted for the larger computer, unwanted data are discarded, and the results are sent on to the larger machine.

Microprocessor computations can also be usefully teamed with specialized mathematical hardware. That is one of the main design ideas embodied in an instrument system now under development at Topanga Data Systems in Woodland Hills, Calif. In this system, a specially designed hardwired high-speed decimal arithmetic unit will take floating-point, binary-coded-decimal data from instruments connected to a standard bus (Fig. 3). Early production units will do addition and subtraction. Later, multiplication and division, along with transcendental function capabilities (such as sine and exponential computations), will be added. These more complex capabilities will be performed with the help of ROM-stored microprograms. Operation of these microprograms and of the high-speed arithmetic unit will be under the control of the same microprocessor that serves to log readings from the instrument bus. About 15 different instruments are to be handled at once by the system, which will take perhaps 100 μs to service each of them. Similar systems have, in the past, been handled by controllers made up of hardwired logic, and necessary arithmetic functions were often performed by calculator chips. With the help of a microprocessor, the power and flexibility of the system are increased, while the integrated circuit package count is reduced.

A system now in use at the Western Electric Research Center in Princeton, N.J., uses a microprocessor to compute means and variances of wire diameter measurements. With these computed results deformation of the wire cross section can be readily detected. For example, any marked elliptical deformation will quickly show up as an increase in mean diameter. Smaller deformations can be sensitively detected, over longer intervals, by observing changes in the variances.

With practically any instrumentation system, calibration is a prerequisite to adequate system peformance, and microprocessors are carving out new roles in this area.

Calibrating with cassettes

Instrument calibration is a wholesale problem in the U.S. Navy. In the past, when a ship came into port, all critical electronic equipment was off-loaded and transported to and from a land-based calibration laboratory. Unfortunately, this transportation process itself would often knock instruments out of calibration after they left the lab. Now a portable, microprocessor-based system allows calibration of equipment on board the Navy ships. Two suitcase-size units—a controller and a calibrator—are connected together to do the work. The link between the two units is an IEEE Std 488-1975 digital interface for programmable instrumentation.

Existing calibration units are for oscilloscopes; similar units are now in development for calibrating voltmeters and signal generators. Calibration routines are stored on cassettes, and are recorded in ASCII code. An interpreter stored in memory translates this information into instructions for the calibrator, allowing it to set up the proper ranges, functions, stimuli, and measurement modes. To perform a calibration, a cassette procedure/program tape is loaded along with a second, blank, data-logging tape. Hard copies of a calibration report can be obtained by plugging an RS-232C compatible printer into the control unit. The printouts are available either during or after the calibration run. Logged cassettes are retained for central records. An optional hand-held control terminal allows the operator to run the system while in a position directly in front of the oscilloscope under test.

A special feature of the calibration controller is a plasma display that incorporates a touch panel keyboard. Operator options are displayed on the panel; by touching the correct spot, desired options can be selected. Among the options are such choices as display of variables or data, selection of logging tape or calibration modes, rewinding of tape decks, or calling for a digital voltmeter reading. This feature, made possible by the microprocessor, considerably simplifies operator training. ◆

Approach with caution

Some smaller companies tend to commit themselves decisively to microprocessor-based designs, moving with characteristic speed to capture as much of the market as they can. Larger companies often tend to move more cautiously and deliberately. For example, at General Electric's Special Purpose Computer Center, Bridgeport, Conn., numerous approaches are being carefully examined during the process of integrating microprocessors into the company's products. Among the important factors that affect their decisions on using microprocessors are the costs involved in training production and maintenance personnel, the costs of maintaining the microprocessor-based products, and the manufactured volume of these products. At very low production volume, the cost of the microprocessor itself (around $30 or thereabout) is much smaller than the design costs for the finished products. The microprocessor chip may then be considered to be essentially a "free" item, according to James T. Duane, manager of that GE Special Purpose Computer Center. Of course, at higher production volumes the cost of the microprocessor becomes more significant.

GE is also concerned with internal standardization of microcomputer hardware and software. The aim is to prevent chaotic proliferation of different designs (dozens of applications of microprocessors have been identified within this giant organization and they have found it rather difficult to convince enthusiastic engineers not to spend their time in "reinventing the wheel" while applying microprocessors in their systems). Among the targets for this intracompany standardization are analog-to-digital (A/D) and digital-to-analog (D/A) converters, and other interface hardware as well.

CAMAC: a modular standard

It began as a tool for the nuclear field. Now this digital interface standard has gone 'real time' in process control and computer networks

With the digital computer extending its sphere of influence from the well-established techniques of business and scientific data processing to real-time data logging, monitoring, and control of scientific experiments and industrial processes, there is a definite need for a computer-independent method of interfacing the process or experiment with the computer. Because a modular approach to interfacing, coupled with the broad benefits derived from standardization, introduces a whole range of advantages to a computer interface system, CAMAC has emerged as a user-developed modular instrumentation and digital interfacing standard that is particularly appropriate for computer-oriented data and control systems.

This article describes the basic IEEE specifications of CAMAC, acquaints practicing system engineers with its basic principles and applications, and gives insight into how this standard can benefit the digital engineering community.

Why a modular standard?

In a real-time environment involving the connection of a computer to physical processes in the real world via transducers or interfaces, the nature of each interface depends on the type of physical phenomenon to be measured. On the other hand, the interface must also relate to the computer as well, which it does through an input/output (I/O) bus or computer port.

One efficient way to handle the connection of computers to a real-time process is by a standard interface designed and built independently of any particular computer I/O port or packaging method (see Fig. 1). The efficiency of this approach can be readily appreciated by looking at a 14-bit analog-to-digital (A/D) converter. Using a computer-independent interface standard, such a converter requires only one module to be designed for a particular application instead of a distinct 14-bit A/D subsystem for each computer—and with no improvement in performance or change in function.

There are many advantages to *modularity*. Not only does it make possible rapid system modifications to meet new demands, but functional modules can be independently tested before they become a part of a complex system, thus saving valuable system checkout time. Moreover, maintenance modules can be rapidly exchanged to minimize system down time.

If *standardization* is added to modularity, the advantages become even greater. As already illustrated by our 14-bit A/D converter example, one standardized module can be used for many computer systems, resulting in larger volume, less custom engineering, and eventually lower price to the user. An equally significant benefit is the wider variety of functional modules available to the system designer (Table I), since many organizations are now making compatible modules with a spectrum of products (Table II).

In addition, the sharing of functional modules between systems defers their obsolescence, reducing unnecessary design changes, a feature that is especially attractive to large organizations responsible for the operation of many systems. Central stocking and ease of transfer of such functional modules make maintenance and development far more manageable for such an organization.

At the present time, the types and variety of components and subsystems available in the United States are increasing rapidly in answer to stimuli from users. Most suppliers will respond rapidly to demand for new items, especially functional modules, which often are developed in direct response to user specifications. For example, modules such as stepping motor controllers, synchro controllers, and I/O modules with relay or optical coupler isolation have recently been generated in response to user requests from the process control industry. The func-

Dale Horelick, R. S. Larsen
Stanford Linear Accelerator Center,
Stanford University

How it started!

Of the two standards recently adopted by the IEEE in the area of digital interfacing, the first (IEEE Std 488-1975) provides a standardized interface for programmable instruments and has been described in previous *Spectrum* articles (see Loughry, D. C., "What makes a good interface," *IEEE Spectrum*, pp. 52–57, Nov. 1974; and Knoblock, D. E., *et al.*, "Insight into interfacing," *IEEE Spectrum*, pp. 50–57, May 1975). The second, commonly called CAMAC (IEEE Std 583-1975, IEEE Std 595-1975, and IEEE Std 596-1975), has had widespread application over the past six years in nuclear laboratories prior to IEEE adoption.

Originally developed by European Standards on Nuclear Electronics (ESONE) in 1969, the CAMAC standard was further developed in collaboration with the National Instrumentation Methods (NIM) Committee in the U.S. Because of its general nature, however, CAMAC is now beginning to be used in medical research, astronomical studies, and industrial process control, among many other applications.

At present, there are about 70 companies throughout the world offering CAMAC products, and a wide variety of functional modules and system components now exists. All elements of the CAMAC standard are nonproprietary, and to use or sell CAMAC products no license or royalty is needed.

tional listings shown in Table I are necessarily brief; however, even with the present small manufacturing base, a system engineer can assemble a real-time system for many popular minicomputers.

Thus, the desirable elements of a modular standard are effective packaging, functional interchangeability, and electrical compatibility, features that allow systems to be implemented using off-the-shelf interface modules that are computer-independent.

How it works

The basis of the CAMAC system is the "crate" that houses the interfacing modules. Figure 2 shows a typical crate and modules meeting the standard. At the rear of the crate is a dataway or mother-board that provides a digital pathway between the modules (usually a printed multilayer board) through an 86-pin connector on each module. It is this dataway that must be carefully standardized to ensure interchangeability of modules, yet generalized enough to permit the various functions necessary for the modules to control and/or measure physical processes in the real world.

Specifically, the crate contains up to 25 connectors to receive up to 25 modules, which may be of multiple width to accommodate varying complexities or to provide varying front-panel space. What is inside the modules is not specified in any way; only the *interface* to the dataway is standardized. (Figure 3 illustrates the nature of this interface.) The single interface to the external computer, controller, or additional crates is made via a module inserted at the right side of the crate (the *crate controller*). Crate operations have a 1-μs (minimum) cycle time.

With the advent of microprocessors, a controller or microcomputer can be housed in the crate controller, in which case there need not be an interface through the crate controller—all of the intelligence is in the crate controller itself.

It should be emphasized that the exact nature of the crate controller is not defined in the basic definition of the CAMAC standard; only the interface to the dataway is standardized. Other CAMAC documents *do* specify several types of crate controllers that are considered "standard," but *any* crate controller conforming to IEEE Std 583 will permit interchangeability of modules, a primary goal of the standard.

Actually, CAMAC is a set of documents describing several system organizations and/or levels of compatibility. Of these standards, IEEE Std 583 describes the crate-module pair, IEEE Std 596 is a high-speed approach to interconnecting up to seven crates (a parallel "highway" consisting of 66 twisted pairs), and IEEE Std 595 (a serial highway) provides the system designer with a powerful option for slower-rate applications requiring large-distance bit or byte serial-data transfers between up to 62 crates (based on a unidirectional loop). Interestingly enough, IEEE Std 595 specifies signal standards based on the new balanced EIA RS-422 standard, but other forms of serial communication between crates are possible using adapters; in fact, at the Atlantic Richfield Hanford Laboratories, crates communicate via a two-way laser link over a distance of 2 km (see Scaief, C. C., III, and Troyer, G. L., "A CAMAC serial highway utilizing a laser link," *IEEE Trans. Nuclear Science*, p. 499, Feb. 1975). The serial method of interconnection has been of particular interest to industrial users in the field of process control since it is well suited to communication and control within a large industrial process plant.

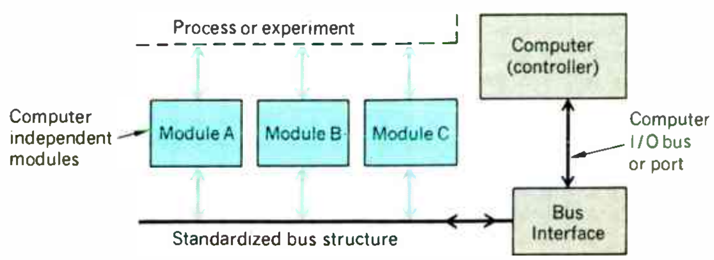
There are still other elements of the CAMAC standard: In January of last year, a software standardization was published that gives users a common language in dealing with CAMAC systems [ERDA Report TID-26615: CAMAC, The Definition of IML, A Language for Use in CAMAC Systems, 1975 (Y3AT7:22/TID-26615)]; and a specification [AEC Report TID-26614: CAMAC, Specification of Amplitude Analog Signals

I. Sampling of commercially available CAMAC hardware

1. *Modules—general purpose*
   - Counters
   - Counters—preset
   - Timers
   - Input register—parallel
   - Input register—serial
   - Input—output register
   - Input register—isolated
   - Clock generators
   - Pulse generators
   - Word generators
   - DVM modules
   - Pulse duration demodulator
   - Output register—parallel
   - Output register—serial
   - Output register—isolated
   - Stepping motor controller
   - Output register—relay
   - Dataway display module
   - Look-at-me (LAM) grader
2. *Multiplexers and converter modules*
   - Analog multiplexer
   - Sample-and-hold multiplexer
   - Analog–digital converter
   - Time–digital converter
   - Digital–analog converter
   - Synchro–digital converter
   - Integrator–ADC
   - Digital multiplexer
   - Code converter module
3. *Peripheral interface modules*
   - Paper tape reader
   - Card reader
   - Line printer
   - Cassette tape control
   - TTY control
   - CAMAC—CAMAC data link
   - Graphic display
   - Display plotter
   - Display vector generator
   - Display systems
   - Serial I/O register
   - Buffer memory
   - Magnetic tape control
4. *Crate controller modules*
   - Type A-1 parallel
   - Type L-1 serial
   - Dedicated single-crate* (type U) for:
     - DEC PDP-8
     - DEC PDP-11
     - DG Nova
     - HP 2100 series
     - Varian 620 series
     - Mod comp
   - Manual crate controller
   - Autonomous or microprocessor single-crate controller
5. *Branch drivers, extenders*
   - Parallel branch drivers for*:
     - DEC PDP-8
     - DEC PDP-9
     - DEC PDP-11
     - DEC PDP-15
     - HP 2100 series
     - Varian 620 series
     - DG Nova/Supernova
     - Interdata 70 series
     - Honeywell 316/516
     - Siemens 320/330, 404/3
     - General Automation SPC16
     - Microdata 800/CIP 2000
     - Autonomous Systems
     - Prime Computers
   - Parallel branch extender
   - Serial branch driver
   - Serial branch extender
   - Serial driver—manual
6. *Crates and associated hardware*
   - Crates, powered
   - Crates, unpowered
   - Module kits
   - Power supplies

*Although Table II gives a list of manufacturers, some of these products are available directly from computer firms.

[1] At the heart of the CAMAC standard lies a standardized bus structure, allowing the use of computer-independent modules to interface the real world.



II. United States suppliers

1. Bi-Ra Systems Inc.
   3520 D Pan American
   Freeway, N.E.
   Albuquerque, N.Mex. 87107
2. Digital Equipment Corp.
   146 Main Street
   Maynard, Mass. 01754
3. EGG/ORTEC, Inc.
   500 Midland Road
   Oak Ridge, Tenn. 37830
4. General Automation, Inc.
   1055 SE Street
   Anaheim, Calif. 92803
5. Joerger Enterprises
   32 New York Avenue
   Westbury, N.Y. 11590
6. Jorway Corp.
   27 Bond Street
   Westbury, N.Y. 11590
7. Kinetic Systems Corp.
   Maryknoll Drive
   Lockport, Ill. 60441
8. LeCroy Research Systems
   Corp.
   126 North Route 303
   West Nyack, N.Y. 10994
9. Nuclear Enterprises, Inc.
   935 Terminal Way
   San Carlos, Calif. 94070
10. Nuclear Specialties, Inc.
    6341 Scarlett Court
    Dublin, Calif. 94566
11. Standard Engineering Corp.
    44800 Industrial Drive
    Fremont, Calif. 94538
12. Tektronix, Inc.
    P.O. Box 500
    Beaverton, Oreg. 97005
13. Packard Instrument Co., Inc.
    2200 Warrenville Road
    Downers Grove, Ill. 60515

Within a 50 Ω System, 1974 (Y3AT7:22/TID-26614)] has been published for analog signals for compatibility with CAMAC modules (at present, only single-ended 50-ohm systems are covered, with guidelines now being developed for other industrial applications).

Some typical applications

CAMAC has been implemented in a broad range of applications and at a variety of levels, from stand-alone subsystems to complete real-time computer control systems. Because of CAMAC's history, many of today's applications are found in a nuclear laboratory environment. However, with the introduction of the standard serial system, industrial and commercial users are realizing the potential benefits of such a standard.

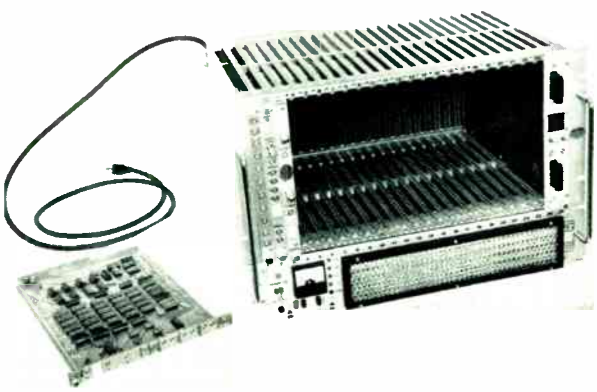
In the field of industrial process control, a large process control system was installed recently by the Aluminum Company of America (ALCOA) at its Warrick, Ind., plant. Consisting of 23 crates controlling 45 ingot-preheating furnaces (each crate housed in a NEMA 12 enclosure), the system features a serial highway with a backup loop operating over coaxial cable at a 500-kbaud data rate, with clock and data transmitted over the same cable. The serial highway employs standard type L-1 serial controllers, driven by a ModComp II computer with a completely redundant backup computer and automatic I/O switchover. Conventional computer peripherals are interfaced via the computer manufacturer's hardware and software, with the system operating in a direct digital control (DDC) mode. All components of the system including the serial highway driver are commercially built, and all of the instrumentation modules used are second-sourced.

Other systems either in operation or under development include a computerized test facility at General Motors' Electromotive Division, and a computerized slab caster at Inland Steel. A number of other large companies are currently considering CAMAC systems.

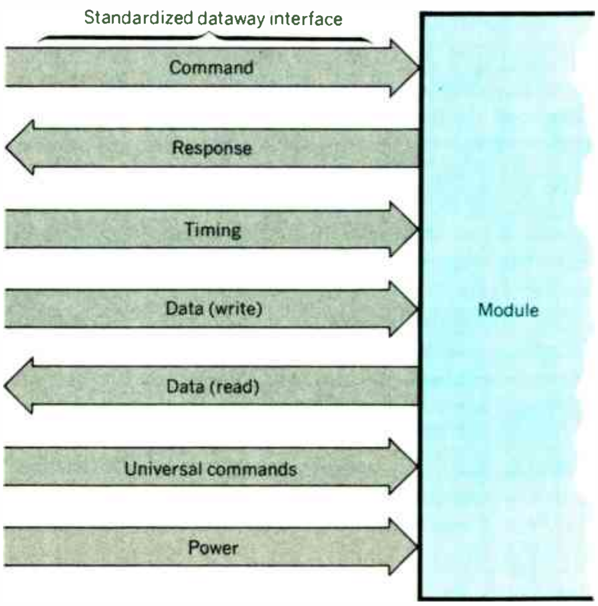
A second area where CAMAC can prove useful is data acquistion. The simplest implementations for CAMAC are those where it is used to add on to, or substitute, part of an existing system. An example can be seen in Fig. 4, which shows a large time-shared machine control and multiuser data-acquistion system at the Stanford Linear Accelerator Center (SLAC). Simplified CAMAC branches have been added via existing multiplexer port interfaces, and operate under program control. The data modules being used are a combination of commercial and custom units, and include nanosecond time-interval digitizers, multichannel 10-bit A/D converters for fast-pulse area measurements, and multiple-pulse input time digitizers (time interval measurement) for use with a particular type of detector. An improvement program is now underway to allow this system to preprocess CAMAC information using microprocessors, and to permit faster read-in using direct memory access (DMA). The modules and branch will remain unchanged, however.

At Stanford University, Xerox Research Division used a small, single-user data acquistion system, directly interfacing computer peripherals with a PDP-11/40 computer on the DEC Unibus. Most data were

[2] A typical self-powered CAMAC crate with modules. A fully powered crate (±6 volts at 40 amperes, and ±24 volts at 6 amperes) costs about $1500, and an unpowered crate about $700 (single quantities).



[3] The basic dataway interface to a CAMAC module. Note that all signals are TTL levels, with power voltages ±6 volts and/or ±24 volts.



acquired through commercially available CAMAC modules, and the system uses a standard parallel highway interfaced via a commercial microprogrammed branch driver. Essentially no hardware was custom-designed for this system. The user's main task for the data acquisition section was to develop a software driver for the CAMAC interface.

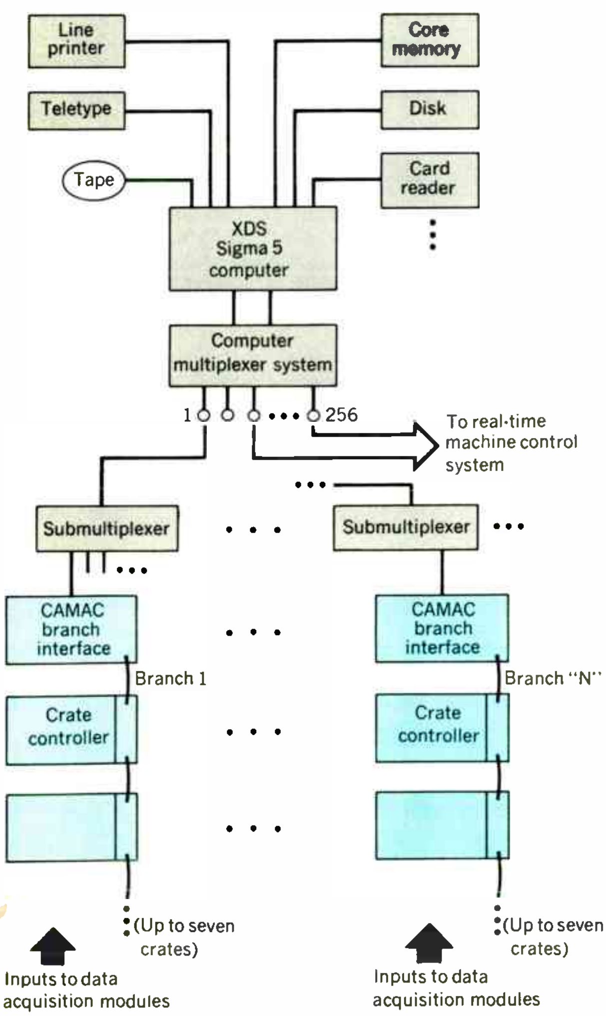
Figure 5 shows a control and monitoring system for large dc power supplies for magnets in accelerator beamlines, an application that is typical of an industrial process-control problem, such as control of a rolling mill. The system is complicated by the fact that a number of independent control points require access to different subsystems over the same CAMAC branch. Also, reassignment of supplies to different control points (users) is sometimes required. This system was built to replace a hardwired system with four main goals in mind: (1) to eliminate a large number of hardwired control/monitoring cables; (2) to reduce system reconfiguration problems by using software reassignment of supplies to each user, plus a possible relocation of a CRT terminal; (3) to provide rapid setting and polarity-reversing capability of systems of supplies, saving expensive experimental accelerator operating time, and significantly reducing energy consumption by rapid turn off/on during idle periods and start-up; and (4) to standardize power supply control hardware and interfaces, thus simplifying further expansion of the system, providing better centrally located diagnostics capability, and simplifying field maintenance and training problems.

Most CAMAC modules were custom-built to optimize design of the functional modules for a large system. Standard peripherals, such as the CRT terminals, Teletypewriter, etc., are interfaced directly via manufacturer's hardware in order to fully utilize available software. The external controllable devices, most of which are located in remote areas, are interfaced on a modified parallel highway.

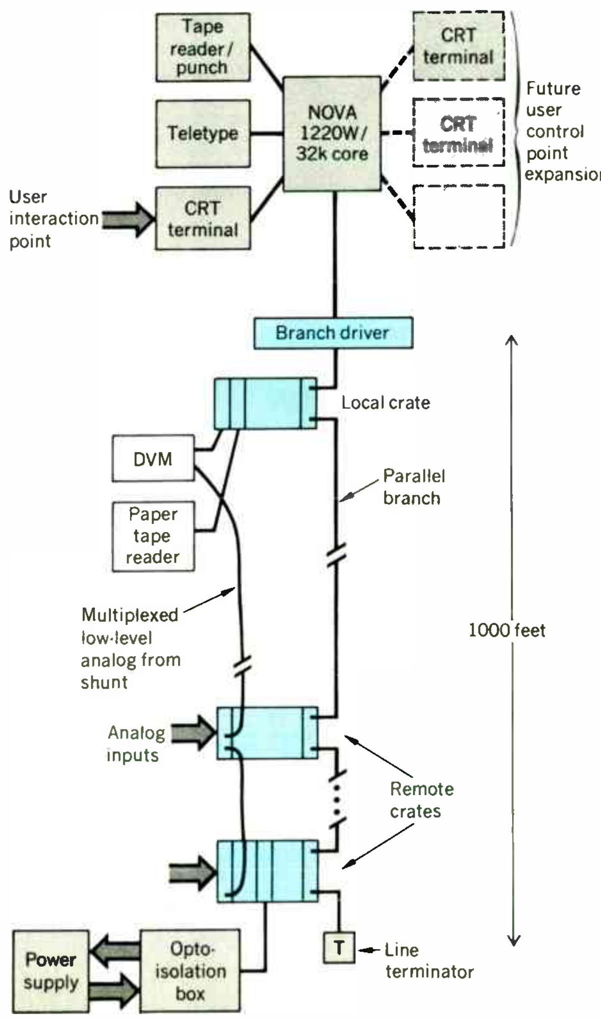
The system is presently working with a single-user control point, but expansion to two additional users is planned. The present highway in use for the initial testing phase is parallel, but when the system is expanded it is planned to change to bit-serial transmission for cabling simplicity, since the data rate is compatible with the serial system. Needless to say, the same modules will be used.

A fourth area of application has been demonstrated at Daresbury Laboratory in England, where CAMAC has been used to interface standard peripherals as well as computer–computer links in a computer network. This network consists of a central IBM 370/165 processor, a variety of minicomputers supervising experimental data acquistion, a control computer for a large

[4] **In this large multiuser data acquistion system, all experimental data from real-world detectors are entered via CAMAC modules.**



[5] **In this long-range system for computer control and monitoring of dc magnets, full photon-coupled isolation is provided between the magnets and the CAMAC crates.**



Fundamentals of IEEE Std 583

The concept of the *crate-module pair* is fundamental to the CAMAC standard. The crate itself is a housing for the modules and the home of the dataway, or motherboard, which is simply an interconnection method for the modules and the crate controller. All signals on the dataway are digital with standard TTL levels. As shown in Fig. A, the dataway is composed of bussed connections *except* for the station lines *N*, and look-at-me (LAM, or service request) lines, which are individual point-to-point connections between each of the module stations and the crate controller. The *N* line, when active or "1," indicates to the respective module that the command on the command bus pertains to that module. Likewise, the *L* line when active indicates to the crate controller that the respective module requires service. Note that the use of individual lines for *N* and *L* permits simultaneous actions in many modules.

Multiplexing from the modules is accomplished by open collector gates. That is, all data transferring from the module to the dataway are transferred via open collector gates such as the SN7401; in turn, the entire crate acts as an intrinsic multiplexer when these gates in the modules are controlled by the respective *N* lines. For data transfer from the dataway to the module, the crate acts as a "distributor." In this case, the *N* lines control which module or modules accept the data.

The basic crate controller module interface is shown in Fig. B. The command lines include five function code and four subaddress lines. The five function code lines are coded into 32 function codes, of which about half are defined to achieve a degree of operational compatibility between modules. For example, *F*(0) is defined as "read data from a module"; *F*(16) is "write data to a module." The four subaddress lines are used to subdivide the module into 16 entities, referred to as "registers," but in a broader sense they are simply "subdivisions." To give an example, *F*(0), *A*(0), reads data from one register, where *F*(0), *A*(1), reads data from another register in that module. The subaddress entities need not be parallel arrays. For example, *F*(25), *A*(0), means "execute" (which might mean send out a pulse) on channel 0; *F*(25), *A*(1), means execute on channel 1 (send out a pulse on channel 1).

Commands are addressed; that is, they are performed only in those modules where the *N* line indicates to do so. There are also *unaddressed* commands, sent as single line commands, which apply to *all* modules; these in particular are Initialize (*Z*), Clear (*C*), Inhibit (*I*), Busy (*B*). The first three have obvious meanings, the last signifies that a dataway cycle is in progress or an unaddressed command is being sent.

A dataway cycle includes two timing signals, *S*1 and *S*2, usually generated by the crate controller. *S*1 is used as a strobe to accept data from the dataway; *S*2 is used for initiating actions that may change the state of the dataway read or write lines. Thus, it is apparent that the CAMAC cycle is a synchronous two-phase timing sequence where data are read or loaded (transferred) on *S*1, and changed (cleared or sequenced) on *S*2. There is no standard cycle time, but a minimum of 1 μs is specified, and all modules must meet this specification to achieve full interchangeability of modules in systems.

All data are transferred within a crate in parallel format. There are 24 read lines and 24 write lines; thus, up to 24 bit parallel transfers are handled. Although there is no specification on a "preferred" word size or type of coding, it is suggested that crate controllers handle the full 24 bits so that all possible modules can be serviced. Binary data coding has, of course, been predominantly utilized.

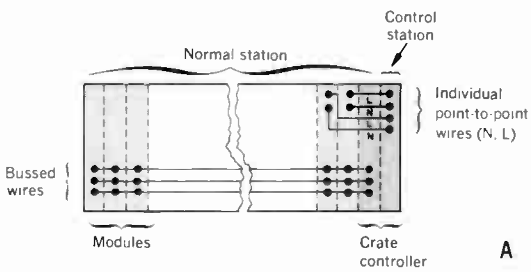
Note that the word "data" is used loosely here—the terms "read" and "write" only imply direction of transfer and the data may actually be control information. For example, *F*(16) (Write Group 1 Register) may be used to send 24 bits of individual on–off information to a register in a module, from which the signals are sent to the process under control.

Two response bits are specified that return from a module via two busses. The first, *X*, is defined as "command accepted." This is simply an affirmation that a module is present in the designated station, and is equipped to do the action required; that is, the particular function code and subaddress are present. The *Q* response bit is not so rigidly defined, and in fact is a generalized response signal to be used as the designer sees fit. In addition, certain function codes used to test features of the module use the *Q* bit to send the yes–no reply. Another use of the *Q* bit is as a control for block transfers. (Three types of block transfers using *Q* are defined in IEEE Std 583.)

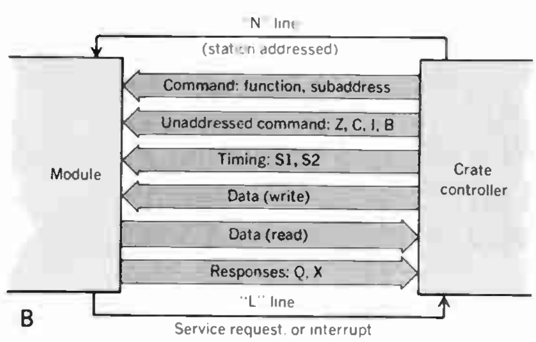
As mentioned previously, the *L* line is the source of an interrupt request from a module. The use of individual *L* lines allows immediate identification of a request. However, in the general case, many different interrupt requests may be generated within a module, all OR'ed onto the single *L* line. The standard provides guidelines for the control and rapid identification of these multiple interrupts.

Although there are several methods that are suggested, probably the most powerful is to treat the interrupts in a parallel fashion and then read and control interrupt registers using the read and write lines as parallel data. For example, using *F*(1) and *A*(14) reads interrupt requests directly using the read lines; using *F*(17) *A*(13) writes into an interrupt mask register in the module. These operations permit up to 24 interrupts in a module—more than sufficient for most applications.

Along with all of these digital signals for conveying information, the dataway also provides power for the modules. The standard voltages are +6 volts, −6 volts, +24 volts, and −24 volts. Additional pins have been assigned for +12 volts, −12 volts, 117 volts ac, and +200 volts, but these are considered special voltages not normally required.



A



B

Where to get CAMAC information

Athough the IEEE CAMAC standards discussed in this article are available from the IEEE directly, the other documents mentioned must be obtained through the U.S. Government Printing Office, Washington, D.C. Additional information, including CAMAC product lists, and any technical questions concerning CAMAC committee activities may be addressed to Louis Costrell, National Bureau of Standards, Washington, D.C. 20234.

Other sources of information are beginning to become plentiful. The *CAMAC Bulletin*, published three times a year, is devoted to CAMAC activities and technical developments, periodically listing commercial CAMAC products (by function) and user-developed software. Subscriptions are available through the Commission des Communautes Europeennes, D.G. VIII 29 rue Aldringen, Luxembourg.

There have been many articles on CAMAC published in the professional literature, including the *IEEE Transactions on Nuclear Science* (see "Proceedings of 1973 Nuclear Science Symposium," *IEEE Trans. Nuclear Science*, vol. NS-21, Feb. 1974; and "Proceedings of 1974 Nuclear Science Symposium," *IEEE Trans. Nuclear Science*, vol. NS-23, Feb. 1975); several tutorial pieces ("CAMAC Tutorial Issue," *IEEE Trans. Nuclear Science*, vol. NS-20, Apr. 1973; and Stuckenberg, H. J., "CAMAC for newcomers," CAMAC Bulletin No. 13 Supplement A, Sept. 1975); and recent survey articles (Mack, D., and Wagner, L., "Application and development of CAMAC in North America in 1975," LBL-3819, May 9, 1975; and Horelick, D., and Larsen, R. S., "Status of CAMAC in North America, 1975," SLAC-PUB-1642, Sept. 1975.). Many diverse applications, such as process control, medical research, and laboratory automation, may be found in these references.

Occasionally, IEEE gives full-day tutorial sessions on the CAMAC standards throughout the U.S. Those interested in the CAMAC Industry Applications Group should contact Dale Zobrist, who is located in the ALCOA Building, Pittsburgh, Pa. 15219.

accelerator, and links to remote job-entry work stations using interactive CRT terminals. High-speed data links are implemented via CAMAC modules in remotely located crates. A long-range microwave link to a remote entry station has also been implemented. A set of macro instructions has been standardized to facilitate implementation of interface software and to maximize transportability of high-level languages between different computers in the system. Peripherals that have been interfaced via this system include paper tape equipment, ROM modules, moving head disks, line printers, CRT terminals, high-speed plotters, card and badge readers, and modem drivers.

Where we go from here

The standards groups that are presently involved in CAMAC (NIM and ESONE) are continuing to pursue new activities. Among these is the preparation of a report on block transfers in CAMAC to limit the number of different block transfer modes that are now possible, thereby simplifying controllers and interfaces and aiding the module designer in selecting a mode of operation.

The software group in particular is currently working on two projects: Fortran callable subroutines for CAMAC operation using IML-related semantics, and extensions of Basic to include CAMAC operations. These developments should give software designers guidelines to achieve new levels of compatibility in CAMAC system software. They are due to be published soon.

Also under active development is a CAMAC software handbook that will introduce CAMAC from a software point of view; it will contain both existing standard software and a catalog of user-developed software such as I/O handlers, operating systems, and multitask handlers. In addition, methods are under consideration for making software, including computer-dependent user-developed software, available through organizations such as the Argonne Code Center, DECUS, NASA, and others. Some software of this type is already available through DECUS and CAMAC manufacturers.

Another activity of particular interest to IEEE is the study of the relation of the CAMAC standard to other digital standards—in particular, the "interface" between CAMAC and the recently published IEEE Std 488 for programmable instruments. In fact, the Los Alamos Scientific Laboratory has built a CAMAC module to interface the IEEE Std 488 bus; it is expected that such a module will become commercially available (see "A new standard for instrumentation interface," *IEEE Trans. Instrumentation and Measurements*, p. 325, Dec. 1975).

Recently initiated is a study of the impact of microprocessors on CAMAC. As previously discussed, microprocessor crate controllers already are in use; however, the new activity is aimed at fully realizing the potential of *distributed* control (multiple sources of control) within the CAMAC structure.

Finally, the CAMAC Industry Applications Group (CIAG) is studying applications of CAMAC to process control. Items of interest include the additional packaging appropriate for that environment, as well as proper techniques of grounding, shielding, and cable termination. ◆

Dale Horelick (M) is a digital systems engineer with the electronics instrumentation group at the Stanford Linear Accelerator Center of Stanford University, Palo Alto, Calif. Prior to this, he was at Lockhead Missiles and Space Division, Sunnyvale, Calif., and ITT Laboratories, Nutley, N.J. He received the B.S. and M.S. degrees in electrical engineering from Carnegie-Mellon University in Pittsburgh, Pa., and has been a member of the NIM committee for eight years, becoming involved in many projects employing the CAMAC standard during this time.

R. S. Larsen (M) is head of the electronics instrumentation group of the Stanford Linear Accelerator Center. He is a member of the IEEE Nuclear and Plasma Sciences Society and has served on the S-NPS AdCom (1970–1974), chaired the S-NPS Committee on Continuing Engineering Education (1970–1974), and was the San Francisco S-NPS Chapter secretary (1971) and chairman (1972). He was also general chairman of the 1975 Nuclear Science Symposium in San Francisco, and since 1966 has served on the NIM committee. Mr. Larsen received the B.A.Sc. and M.A.Sc. degrees from the University of British Columbia, and the degree of engineer from Stanford University, all in electrical engineering.

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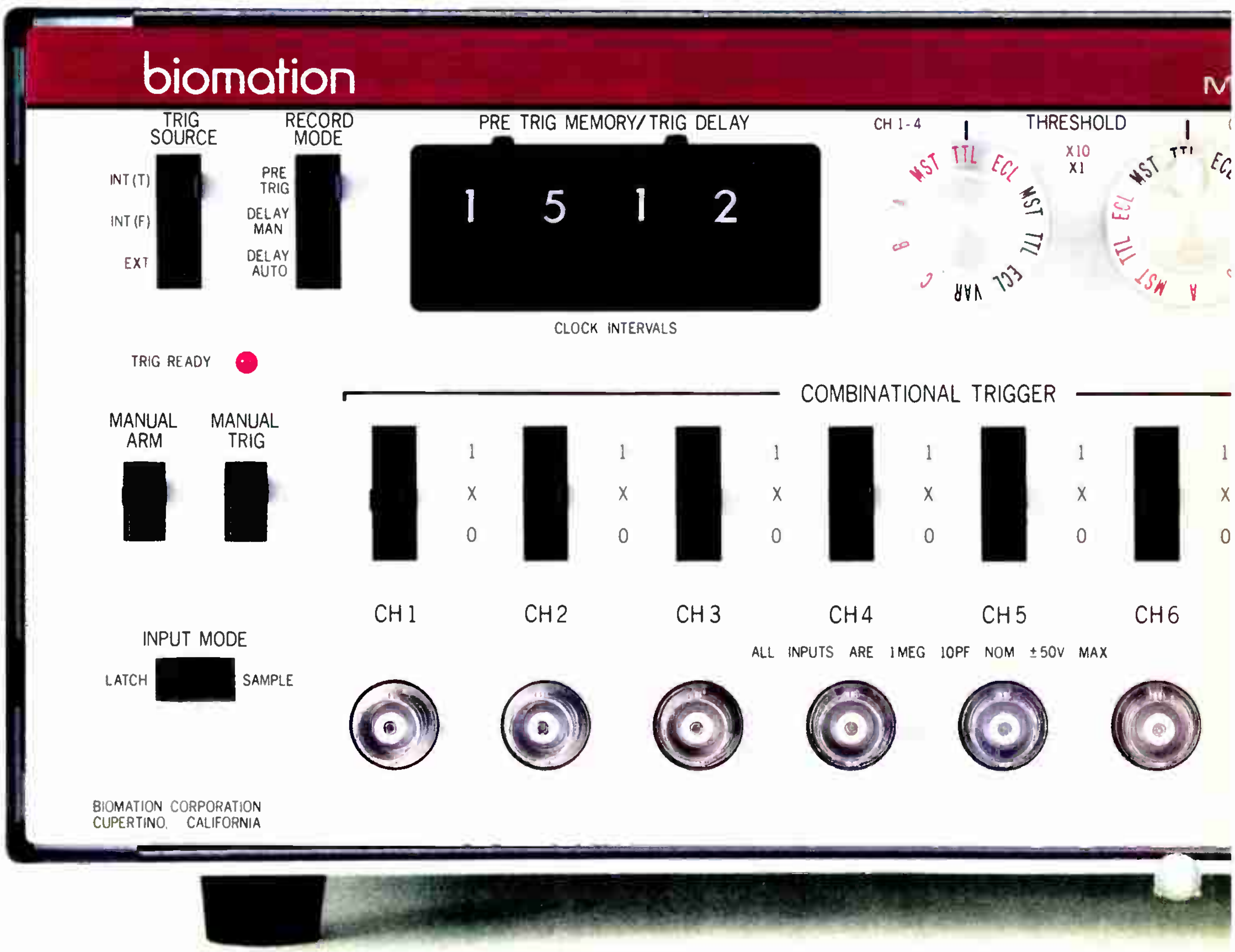

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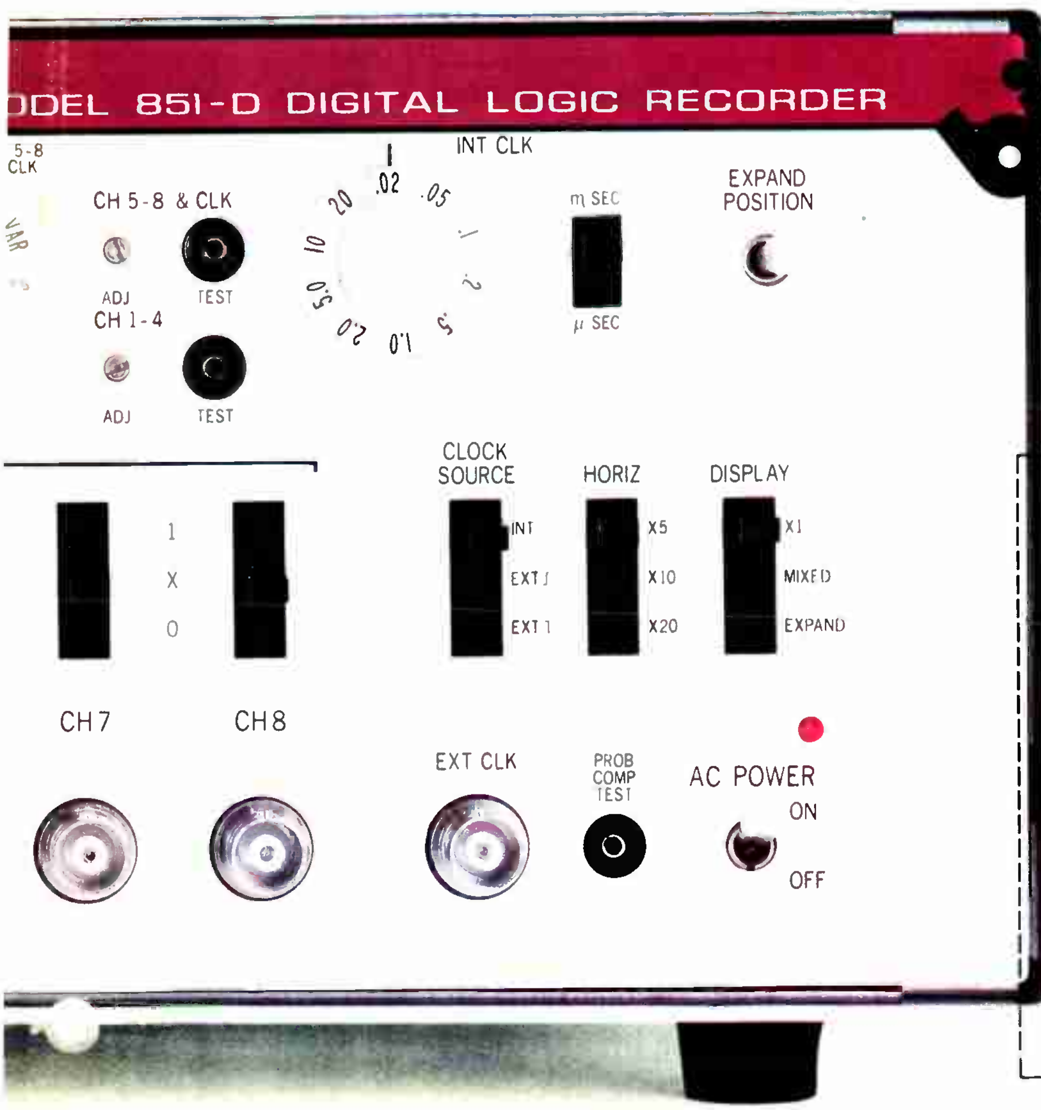

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ICs: from sensors to displays

Instrument performance is up, costs are down. It's done, not with mirrors, but with integrated circuits

From small simple digital panel meters to large sophisticated test systems, integrated circuits continue to have a vast impact on improvements in instrument performance. Entire generations of new instruments have come into existence, thanks to monolithic ICs. Sophisticated logic analyzers, low-cost frequency synthesizers and counters, wide-band oscilloscopes, and truly portable instruments of all types are a few of the more obvious examples. The driving force behind all this has been the continuous increase in IC-device volumetric efficiency—putting down more electronic circuits on smaller IC chips. Starting with the first ICs of the early '60s, solid-state monolithic technology has continued to evolve from SSI to MSI to today's LSI ICs. LSI microprocessors, for example, are creating a new generation of "smart" instruments.

Monolithic ICs can be found just about everywhere in instrument circuits, generally providing equal or better performance than possible with other means, and at lower prices.

But monolithic ICs are by no means the only answer to all instrument circuit-design challenges. Advances in hybrid ICs, thick- and thin-film circuits, discrete components, and innovative circuit-design ideas are all contributing to making better instruments. In fact, in many instrument circuits, using discrete components is the only way to achieve needed performance levels in a practical manner. Nevertheless, monolithic ICs are slowly replacing greater numbers of discrete components, as integrated-circuit technology matures.

From small to miniature to . . . ?

The most obvious and dramatic result of the use of ICs in test and measurement instruments has been the miniaturization of these instruments—despite the fact that significantly better performance and lower prices have accompanied the shrinking process. Many once bulky, single-function instruments weighing 25 kg or more have been replaced by small multifunction instruments with even better performance for less money. Function generators and miniscopes are good examples. The latter, a new class of service oscilloscopes available from Tektronix, Vu-Data, and Philips Instruments, have been reduced in size and weight to such levels that the batteries that power them weigh as much as the electronics and often more.

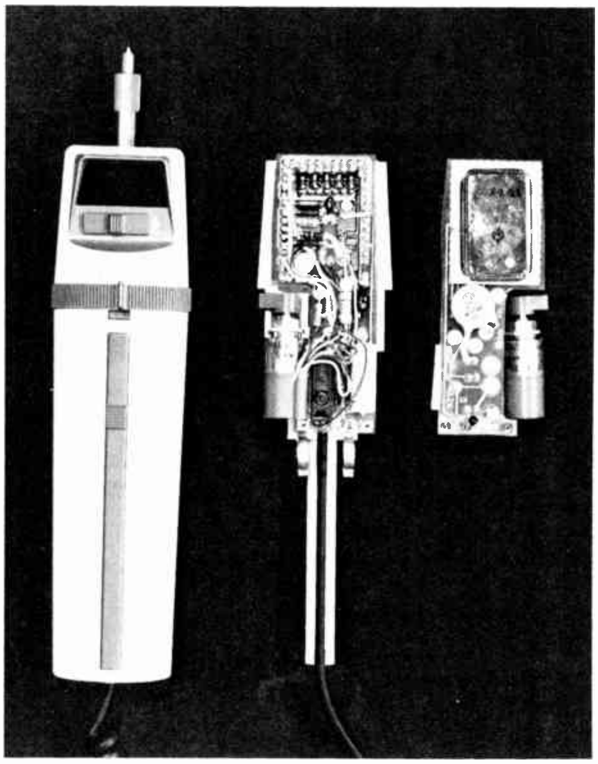
The trend to extremes of miniaturization has also posed other problems. For example, the question of the operator-instrument interface via front-panel switches and knobs is becoming more difficult to solve. And temperature-rise problems surface when too many ICs and components are packed into close quarters, thus contributing to poor reliability. Designers therefore have had to concern themselves more with the proper choice of low-power devices such as CMOS ICs, and with intelligent splitting of analog and digital circuit designs into partitions, thereby reducing heat dissipation and physical size (Fig. 1).

Roger Allan Associate Editor

Linear ICs coming up strong

Because digital-IC technology has tended to outpace linear-IC technology in developments, most ICs found in instrument circuits have tended to be digital. For instrument front-end circuits where linear components are used, whatever ICs that could be found have tended to be custom ICs, an important exception being the op amp. This situation is now beginning to improve, with new linear-IC developments. Instrument front ends can now be designed with wide-bandwidth (up to 500 MHz) devices that are standard items, thanks to DMOS (double-diffused MOS) technology. Single-chip CMOS A/D converters, such as those available from

[1] Hewlett-Packard's model 970A 3½-digit autoranging multimeter is about as small as any such instrument can be designed. The probe-like instrument measures ac and dc voltage and dc resistance (an optional current adapter allows ac and dc measurements). Center and right views show both sides of the 970A's internal circuitry.



Analog Devices and Teledyne Semiconductor, are destined to have an impact on digital-multimeter performance and price. Even single-chip function generators (available from Exar Systems, Intersil, and Interdesign) have come down in price to be considered for possible use in function-generator instruments, despite their inferior performance (performance generally degrades above 10 kHz) as compared with discrete-component designs.

Intersil is currently developing an improved function-generator chip (model 8058) that is said to be vastly better in performance than the company's earlier model 8038 function-generator IC. The device reportedly is easier to use over a 1000:1 VCO (voltage-controlled oscillator) range; is useful up to about 1 MHz; has a sine, square, and triangle output; and dissipates less power than the 8038. It will offer accuracy within 1 to 2 percent (0.3 to 0.5 percent with external trimming), has high repeatability, and will sell for about $3 to $4 each in OEM quantities.

A low-cost function-generator IC chip with decent performance levels can be used in a precision function-generator instrument as a front-end sweep generator for FM and AM capabilities, according to Edward Reamer, engineering manager for Interstate Electronics. He believes it could even be used as an extra auxiliary output for more capability. "It makes little sense to use such a chip as the actual function generator, in place of the conventional discrete-component method, unless the instrument can be sold for a ridiculously low price like $30," he says.

Hickok Electrical Instruments, however, points out that its model 270 function-generator instrument for $185 (formerly introduced at $166) has been selling well. The generator makes use of an Exar model 2206 IC chip for function generation.

Analog Devices is working on linear monolithic ICs that are certain to have an important advantage for instrument designers. These include a 10-bit V/F converter with accuracy within 0.1 percent, and an rms-dc converter for use in voltmeter circuits, making rms measurements possible at low cost.

Although stability and repeatability are two critical performance factors that have yet to be fully satisfied with linear ICs, some designers, such as Arch Conway, development manager for Dana Laboratories, believe that digital ICs can be used to correct accuracy errors of linear ICs.

Progress in monolithic converters

In monolithic A/D and D/A converters, one of the earliest efforts was the PMOS NC0904—a 3½-digit single-chip digital panel meter, made by Nitron under a license from Integrated Photomatrix Ltd. of England. Its drawback was that it required more than a dozen external components in order to function.

Newer units include 8-, 10-, and 12-bit series 8700 CMOS A/D converters from Teledyne Semiconductor that need no external components to operate, and Analog Devices' model AD7570 10-bit CMOS A/D converter, which is microprocessor-compatible. Analog Devices also recently introduced a 13-bit CMOS A/D converter with impressive performance specifications, such as 13-bit accuracy and 1-ppm/°C offset and gain

The IC manufacturers's role

The recent introduction by Fairchild Semiconductor Corp., Mountain View, Calif., of a digital panel-meter (DPM) instrument has sparked speculation among many instrument industry spokesmen about IC manufacturers getting into the instrument business. These spokesmen also point to the invasion of ICs into more and more instrument circuits, particularly LSI, as a further reason why IC manufacturers would eventually become instrument manufacturers. It is also common knowledge that some large instrument manufacturers such as Hewlett-Packard and Tektronix have been manufacturing, and continue to manufacture, many of their own ICs for use in their instruments.

Will the IC manufacturer also become the instrument manufacturer of the future? A careful survey by *Spectrum* of leading spokesmen for both the IC and instrument industries shows it is doubtful that this will happen, except for special cases, like DPMs, where the DPM's wide range of applications (medical, chemical, process-control, and electronic applications are but a few) makes it economically feasible for an IC manufacturer to market it. A DPM is a small instrument that displays measured quantities such as voltage, current, resistance, or other nonelectrical quantities such as force, pressure, etc., scaled in engineering units on the display. DPMs are single-range instruments that generally mount in panel cutouts.

It is volume selling that the IC manufacturer needs to offer low-cost advantages. Furthermore, a DPM is basically simpler than most instruments. In fact, DPMs made up of a few IC chips are possible to manufacture today. DPMs also usually wind up as displays in larger instruments such as analytical instruments.

What is more likely to happen is that the IC manufacturer will become more involved in manufacturing instrument subsystems, made up of one or two IC chips, for use by the instrument manufacturer.

Will this mean that the instrument manufacturer with an in-house facility for making ICs will have an added advantage over those without such a facility? There is no clear-cut answer to this; it all depends on the instrument's intended application. To the manufacturer of high-performance instruments for specialized applications, the need for making his own IC often predominates because such a device either may not be available on the market, or not low enough in cost to buy. On the other hand, IC chips do exist in many functional forms to satisfy the requirements of many general-purpose instrument manufacturers, and it is clearly advantageous to buy ICs on the market under those circumstances.

Even those with an in-house IC capability readily admit that the situation has its pros and cons. As William Kay, Hewlett-Packard's manager of engineering for the Loveland Instrument Division, states: "To some degree an in-house IC-design capability can put some blinders on an instrument manufacturer. On the other hand, to rely on IC manufacturers' designs, an instrument manufacturer might lose a competitive edge. The need to make or buy an IC must therefore be carefully weighed on the basis of what ICs are commercially available, how good they are in performance, how much they cost, and how many other sources make the same ICs."

drifts, at a $25 price (100 quantities). The company credits the development of the model AD7550 to what it calls a "quad slope" conversion technique. The converter requires an external *RC* network and a reference supply to operate.

At the 1976 Solid State Circuits Conference, several companies, including Motorola Semiconductor and RCA's Solid State Division, unveiled monolithic A/D converters. Motorola's MC14433 is a CMOS 3½-digit A/D converter requiring two external resistors and capacitors to operate. It features two voltage ranges of 1.999 volts and 199.9 mV, over 1000 MΩ of input impedance, auto-zero and auto-polarity, ratiometric operation, and 25 conversions/second. RCA's device is a COS/MOS 11-bit A/D converter for low-power applications. It is said to operate from a single 4.5- to 15-volt unregulated power line at 1.2 mA of current drain (V_{DD} = 5 volts).

Two-chip A/D converters have been available for some time, and are helping to enable low-cost portable-instrument designs. For example, Vu-Data uses a two-chip A/D conversion scheme in its model 915/975 oscilloscope with a frequency counter and digital multimeter. According to Vu-Data, this approach made possible 3½-digit A/D conversion for less than $20.

Monolithic D/A converters are commercially available devices that are helping to make more accurate instrument circuits. Such converters allow the setting of signal threshold levels by digital means, for greater precision than was available with conventional methods of using potentiometers.

An important linear-IC development is the National Semiconductor series 155/156/157 internally compensated op amp. Combining JFET and bipolar technologies on the same chip, National produced a low-cost (approximately $2) single-chip op amp with wide bandwidth up to 20 MHz, 30-pA bias current, 3-pA offset current, 1-mV offset voltage, 3-μV/°C offset-voltage drift, and very high input impedance of 10^{12} Ω. The 741-compatible op amp is rated to slow at 50 V/μs.

Another example of linear-IC progress is Harris Semiconductor's model HI509A four-channel differential-input CMOS multiplexer for low-level instrumentation data acquisition. Part of a family of multichannel multiplexers, it offers excellent crosstalk performance and protection from common latchup problems, performance that is the result of Harris' dielectrically isolated CMOS technology.

Digital ICs: better performance

For digital ICs, improvements have tended to be in lower power dissipation, higher complexities, and lower prices. The previously rapid pace of developing higher operating speeds for digital logic ICs has slowed down to about the 0.5-ns gate-delay range, mainly due to a lack of a large number of applications for such ICs and to the high cost of pushing this aspect of the state of the art for low-cost conventional ICs. Often, those in need of such high-speed ICs must either develop their own, or make use of discrete-component designs. Electronic frequency counters are an example. Special 500-ps ECL ICs were developed by Hewlett-Packard for its model 5345A electronic counter to make possible 2-ns measurements.

Low-power Schottky TTL is widely being used in place of older TTL families, like 7400 TTL, in instruments circuits, with lower-power-dissipation advantages. Some designers using low-power Schottky TTL are reporting power-dissipation levels one fourth of those of standard TTL ICs.

Many instrument designers are enthusiastic about the new I^2L ICs, and believe that I^2L will replace ECL (along with some high-speed Schottky TTL, the fastest ICs presently available) in one to two years, as I^2L prices mature.

A mixed blessing for LSI

Not all instrument designers see LSI ICs as without some problems. Some, such as Tektronix's Glenn Sorum, manager of the mechanical engineering group for portable oscilloscopes, feel that because LSI ICs allow local heat concentrations, they produce higher temperature rises than do the non-LSI ICs that take up more space. This makes the problem of heat removal through heat sinking more difficult to solve. For some LSI ICs, Sorum said that he's had to design his own heat sinks.

Sorum also feels that standard LSI ICs with the "same pinout" configuration would inhibit the designer's flexibility. He believes that it is better to use custom LSI ICs for maximum flexibility, even though they might cost a little more.

Another LSI problem is reliability. No specific figures could be obtained, but many instrument designers do complain about poor LSI IC reliability, even at the incoming inspection level.

This reliability problem is certainly not a new phenomenon; it can be expected with any new technology where some very complex devices are being made and equipment to test them properly is hardly available.

William Kay, manager of engineering for Hewlett-Packard's Loveland Instrument Division, feels that as devices such as LSI ICs become more complex, overall circuit reliability increases. How such a device is used ultimately determines its application reliability, he says. He does concede that a better qualification program is needed for LSI IC manufacturers.

Microprocessors change the rules

The impact of the microprocessor IC on instrumentation is already being compared to that of the discrete transistor and the IC. But, unlike the transistor or the IC, the microprocessor is having a more profound impact on instrumentation by altering the rules for instrument product development, from the early phases of planning, through design, and into production (Fig. 2). Software expertise is now a must for designers using microprocessors.

There can be little doubt that the microprocessor is a tremendously valuable design tool. Unfortunately, the concept of a microprocessor all too often has been seized upon by some instrumentation industry spokesman as a "do it all" marvel that should be in every instrument. This situation is analogous to the one that existed during the '60s, when the concept of the phase-locked loop (PLL) was broadly discovered. In those days, because of the PLL's newness and the lack of understanding concerning it, instrument designs without PLLs were considered passé.

Many instrument designers interviewed by *Spectrum* had high praise for the microprocessor, but were careful to point out that in some instruments, such as low-cost (under $300) general-purpose multimeters and function generators, its use is neither practical nor economical. Nor is it necessarily a device for use in all high-priced instruments, as some manufacturers of such microprocessor-based instruments on the market have found out to their dismay. Where the microprocessor really stands out is in its ability to give the instrument user more measurement capability with fewer manual-control manipulations and calculations, for about the same price he had to pay before the microprocessor was used. Operators who lack the expertise and knowledge to handle complex instruments have been a natural market for microprocessor-based instruments. The microprocessor is also helping reduce the hardware complexity of interfacing several instruments together.

Most microprocessor designs in instruments have been dedicated ones, where the user has little or no access to the instruments' stored-program control (e.g., monitoring and controlling). And this is only the tip of the iceberg—the potential applications for microprocessors in instruments where the user has access to the stored-program control of the microprocessor (e.g., signal analysis) are limited only by one's imagination.

One of the biggest costs incurred in using a microprocessor is the cost for software development. And since little standardization exists among available 4- and 8-bit units, it becomes prohibitively costly to switch from one microprocessor development system to another during the initial design stage.

Thick- and thin-film prices drop

Thick- and thin-film technologies have closely followed monolithic IC technology, filling in price/performance gaps. Recent price reductions of thick- and thin-film resistor/capacitor networks have made their use in instrument circuits, to replace discrete components, more practical. For example, Analog Devices' Resistor Products Division sells 8-, 10-, and 12-bit thin-film current and voltage ladder networks that are rated to within ½ LSB over 0 to +70°C for $7.80 each (dual-in-line package), or $6.70 each (at the chip level), in 100 quantities. Advances in automatic laser trimming methods, batch processing, and packaging are making all this possible.

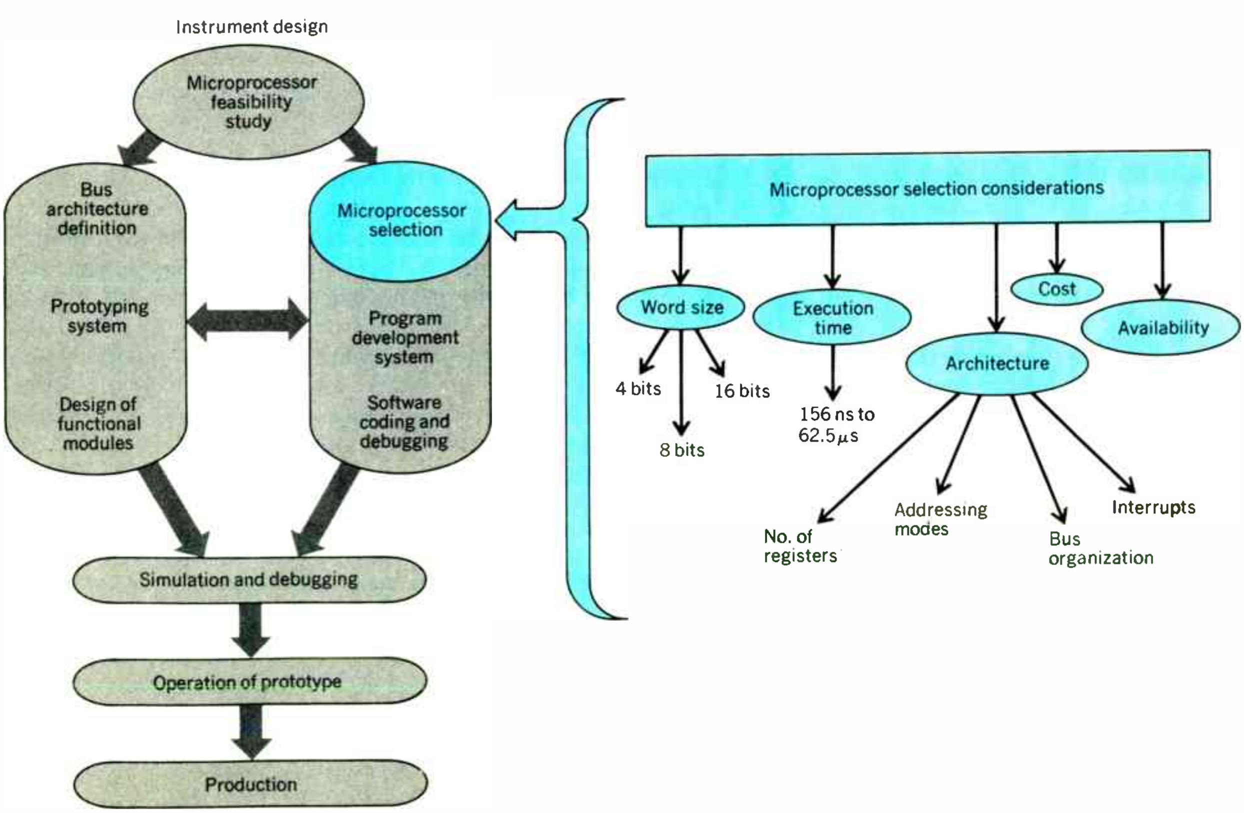
The use of thick and thin films in hybrid ICs is widespread. Wherever a need for high performance exists that cannot be fulfilled by a monolithic IC, it is sure to be met with a hybrid thick- or thin-film IC, particularly at high frequencies. In Hewlett-Packard's model 5345A microwave frequency counter, for example, the input amplifier is a thin-film dc-coupled 10–20-mV op amp pair, designed by Hewlett-Packard engineers, that is matched to within an incredible 700 ps in time.

Hybrid thin-film technology is almost always found in microwave instrument designs. This is true because, above a few gigahertz, parasitic capacitance problems develop using discrete components, and few monolithic ICs can be found that operate at such high frequencies.

LEDs pace instrument displays

Two things have largely contributed to rising LED-display popularity as instrument readouts: improvements in LED efficiency and lower prices per digit. While liquid-crystal and gas-discharge displays continue to be found in some test and measurement instruments, LEDs are the most widely used instrument displays. They offer advantages of operating over wide temperature ranges (a limitation of liquid crystal dis-

[2] A flow chart of how designers of microprocessor-based instruments might proceed. (Source: Thomas A. Rolander and Richard W. Van Saun, John Fluke Mfg. Co., Inc.)



Transducers in instrumentation

Transducer technology has never been noted for rapid advancements. When compared with the explosive advancements of other segments of instrumentation circuitry with which it interfaces, the transducer would seem to be advancing at a snail's pace. But monolithic IC technology is starting to make some inroads in improving transducer performance.

Until recently, most transducers were designed and manufactured by manufacturers who had little or no knowledge of the rest of the transducer's instrumentation circuit. Transducers have generally been custom precision components requiring a high degree of craftsmanship (much like precision watch making), and have tended to be high-priced items. It was left up to the user to match his transducer to a system, or have someone build the entire measurement system from sensor to output at a very high price. One problem has been the instrumentation industry's suspicions and subsequent reluctance to engage the component manufacturer for a better transducer-to-system interface.

Monolithic IC technology is now making possible high-performance precision transducers at low cost with great flexibility, such as those available from National Semiconductor Corp., so that instrumentation circuit designers are finding it easier to choose and use a transducer. Furthermore, the inherent integration advantages of the monolithic process promises future transducer systems in a package, where the sensor and A/D converter can be put on one or more IC chips.

Many reasons exist for monolithic technology being applied to making transducers, but high among them are the new mass-market applications that instrumentation systems are getting into. The field of medicine, the automobile, utilities, avionics, and the heating and ventilating of buildings are just a few applications that require transducers in large numbers for temperature, pressure, and flow sensing. Some argue that new monolithic transducers are in fact creating these markets, but such an argument is academic, for the existence of such transducers and applications are related and inseparable.

Arthur Zias, National Semiconductor's manager of transducer engineering, sees a bright future for the monolithic IC transducer. "As gas, clean water, and clean air become scarce, and more valuable, these materials are going to be more carefully metered into every living unit . . . and to do that, we'll need to measure the temperature and pressure as well as the flow rate to compute and control distribution." Zias foresees more emphasis on doing the signal processing as well as the signal conditioning at the sensor, making the transducer a more integral part of an instrumentation system. Zias says, "In the future, we can't have a little man running around reading meters in your basement. Upon electronic interrogation, the transducer/signal processor should tell how much fluid of each type the living unit used since it was last asked . . . and perhaps report peak flow rate or whatever diagnostic makes sense."

plays, though this is improving), can be multiplexed like gas-discharge displays, and operate from 5-volt logic levels (gas-discharge displays require high voltages).

Improvements in LED processing have brought drive-current requirements down to about 0.1 mA per segment. Several colors are now available, including red, orange, yellow, and green, all at nearly equivalent prices.

For certain very-low-power portable instruments such as Dana Laboratories' Danameter digital multimeter, the miniscule power consumption of a liquid-crystal display (which has been improved down to about 200 nW for a 0.25-in- or 0.68-cm-high field-effect 3½-digit display) makes its use highly desirable. The Danameter's entire circuit is a two-chip MOS/bipolar IC optimized for low-power dissipation of a few milliwatts, most of which is taken up by the instrument's liquid-crystal display.

Gas-discharge displays are generally found in instruments requiring displays that are highly readable from lengthy distances, such as in instruments used on production lines. However, high-efficiency LEDs that are now available up to 1 in (2.54 cm) in height are posing a strong challenge.

The designer's future role

The fantastic growth rate of ICs and other electronic components has very much changed the role of an instrument designer. When discrete transistors first became available at a few cents each, a design objective was to replace as many components with discrete transistors as possible to reduce cost and increase performance. Then came the IC, with the design objective being much the same: use as many low-cost digital ICs as possible in place of discrete transistors. This concept is no longer totally valid. For the microprocessor IC, the rules of the game have changed.

As Zoltan Tarczy-Hornoch, Systron-Donner's Instrument Division director of research puts it, "The trend for instrument designers has now gone from circuit design and logic design to software/hardware integration. It is no longer valid to simply replace one or more components with another more advanced one. The future instrument designer must know how to strike an optimal cost/performance balance between software and hardware."

Designers of instruments will also have to pay more attention to the other phases of an instruments's cycle, such as product planning and production. For example, James Hinze, Tektronix's program manager for portable oscilloscopes, says that in Tektronix's new T900 line of oscilloscopes, designed for lowest cost at moderately high performance, not only was the choice of what type of capacitor to be used important, but also what form it should take to reduce labor costs. In Tektronix's case, tubular machine-insertable capacitors were chosen to facilitate production at low cost. ◆

The author wishes to thank members of the engineering staffs of the following companies for helping him prepare this report: Dana Laboratories, Datel Systems, E-H Research, Hewlett-Packard (Colorado Springs, Loveland Instrument, and Santa Clara Divisions.), Hickok Electrical Instruments, Honeywell Instruments Division, Interstate Electronics, Keithley Instruments, National Semiconductor (Transducer Group), Neff Instruments, Preston Scientific, Systron-Donner Instrument Division, Tektronix, Vu-Data, and Wavetek.

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What's new in test gear

The shopping list of versatile, compact, and cost-efficient instruments is an engineer's delight

Test and measurement instruments today are more sophisticated, are simpler to operate, and provide more measurement capability per dollar than ever before. Progress in integrated-circuit technology and changing market requirements are the major reasons. Today's digital multimeter, for example, can make microvolt measurements at accuracy levels within a few one-hundredths of a percent, at a price of about $200 to $300. Frequency counters that can measure up to 100 MHz and have a variety of other measurement functions (period, totalize, etc.) are now available for just a few hundred dollars. Such instruments were, not too long ago, "big ticket" items with large price tags and could only be found in advanced laboratories.

Many of today's instruments are designed to communicate with each other via appropriate interfaces, a fact that is enhancing their measurement capability. The new IEEE Standard 488 interface, while not a solution to everyone's interface problem, is rapidly gaining in popularity. Currently awaiting approval by the International Electrotechnical Commission, the standard is considered by many instrument users to be a good general start that may eventually spawn other more dedicated interfaces.

Taking a broad look, two trends can be seen in instruments. The first is the movement toward instrument clusters—mini instrument systems—and away from the individual instrument of the past. These instrument systems are either hooked up together with external interface cables, or are tied together on card cages in a single package. The other trend is the development of low-cost dedicated instruments to do well only specific tasks at minimum cost.

A central role for the microprocessor

The microprocessor IC is revolutionizing instrument capability in three basic ways: by providing a greater number of more accurate measurements; by simplifying instrument–instrument interfacing; and by simplifying the operator–instrument interface (see, for example, the first three articles in this issue). Nearly every instrument type is now available with microprocessor control.

With the microprocessor, newer instruments are not only performing such traditional instrument functions as data acquisition and display, but data storage and manipulation as well.

Because the microprocessor is a new device that has yet to mature, its use is being questioned in some cases where a higher price tag results. Although it may be true that the extra cost does not justify microprocessor use in some instruments (the assumption is made here that an equivalent level of performance is possible by other means), the microprocessor is also enabling practical measurements in a variety of instruments where practical measurements were once impossible.

Take the Systron-Donner model 7115 digital multimeter, for example. The instrument's standard capabilities include automatic zeroing, automatic self-calibration based on internal or external voltage and resistance standards, and self-diagnostics of failures or marginal operating conditions. Additional optional features include IEEE 488 or parallel interface, high and low readings, storage and limit comparison, averaging a selected number of readings, and up to third-degree polynomial transformations to linearize or normalize measurements of input signals. A keyboard is also available for manual-program selection and data entry. Some optional capabilities are becoming so popular, according to the manufacturer, that the company is considering making them standard features.

In Hewlett-Packard's model 1722A oscilloscope, a microprocessor makes possible an instrument that not only presents qualitative information, but high-accuracy quantitative data as well. No longer is the oscilloscope a 3-percent instrument as it had been for years. The 1722A's microprocessor remembers control settings, computes all the answers, and displays them on an LED display. It even prevents erroneous measurements by warning the oscilloscope user of illegal control combinations.

Tying it all together

As mentioned earlier, one trend is toward instrument clusters, all tied together to perform highly complex calculations. This trend is gaining momentum, with the microprocessor lending a helping hand. Formerly, expensive and bulky minicomputers were needed to control such systems, limiting them, due to interfacing complexities and associated high costs, to large-scale or high-volume users.

The systems or cluster approach is advantageous in making possible complex measurements, data manipulations, and data decisions with far greater resolution and accuracy than is possible using individual instruments. Intelligence is within the instrument system acting as a whole, not in individual instruments acting separately.

Doric's Digitrend 220 "smart" data-acquisition system provides an instance of this. Under the control of an Intel 8008 microprocessor, the system accepts up to 1000 analog inputs from a variety of sensors, automatically scans these signals sequentially or randomly under external control, and digitizes and displays the results in engineering units. The data can also be

Roger Allan Associate Editor

logged on printed paper tape.

Hewlett-Packard's model 3050B is another example of the instrument cluster. This powerful automatic data-acquisition system under programmable-calculator control includes the company's model 3490A digital multimeter and model 3495A scanner. Interfaceable to the HP-IB bus (Hewlett-Packard's interface version of the IEEE Standard 488), the system provides a low-cost solution to data acquisition and analysis.

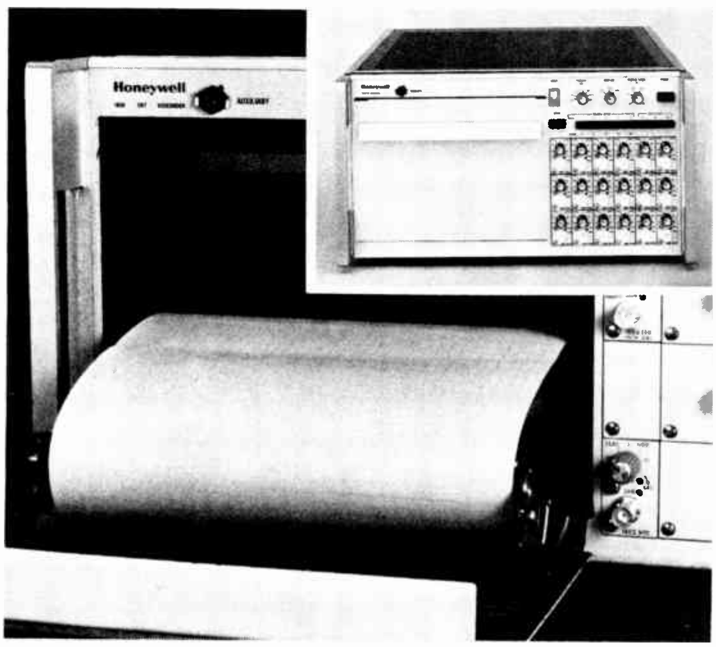
Keithley's System 1, a calculator-based instrument system, even allows peripherals such as disks, cassettes, CRT terminals, and $X-Y$ plotters to be married to the instrument system.

In some microprocessor-based instruments, such as Dana Laboratories' series 9000 timer/counter, one of the original design goals for using a microprocessor was to simplify the instrument's two-way interfacing with other instruments, employing IEEE Standard 488. Many of the counter-timer's new measurement capabilities were developed as a result of the fact that a microprocessor was already being used.

Better instrument–operator interface

Increased instrument operating complexities and emerging new markets with nontechnical users are creating a need for simpler instrument–operator interfacing in instruments. Keyboard entry and digital readout and/or CRT displays that facilitate operator convenience are becoming increasingly common. Dana Laboratories' series 9000 timer/counter and Wavetek's models 152 and 159 function generators with keyboard entries are only three examples. Newer L/C/R bridges, such as Boonton Electronics' model 76A capacitance bridge, do all the work previously done by the operator, autoranging and digitally reading out capacitance values automatically. Dana Laboratories is also giving serious consideration to using a keyboard entry on its line of digital voltmeters, after witnessing the success of it series 9000 counter with keyboard entry.

[1] Data are recorded on this oscillographic recorder's paper by a fiber-optic flat-face CRT (gray top bar seen inside the instrument with its front door open). The instrument (inset) is Honeywell's 18-channel 15-kHz model 1858 oscillograph. The fiber-optic CRT allows more linear, lower-power-dissipating, and higher-speed voltage-sensitive recording than conventional current-sensitive galvanometers.



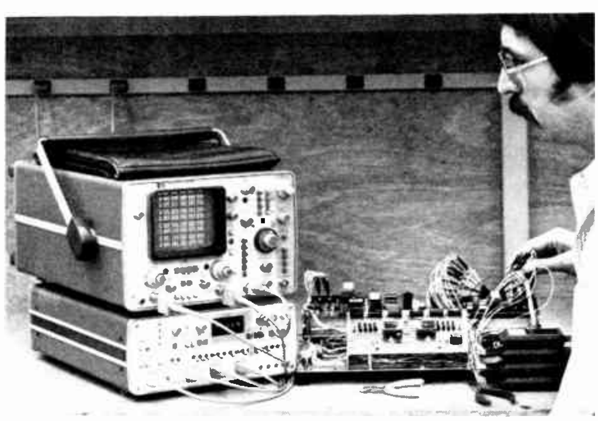
The CRT is also being used to make a better instrument, as is the case with Honeywell's model 1858 oscillograph (Fig. 1). This 18-channel 15-kHz recorder has an internal fiber-optic-CRT recording system that allows more linear, lower-power-dissipating, and higher-speed voltage-sensitive recording than the older, conventional technique of using current-sensitive galvanometers. The fiber-optic-CRT recording technique, also used on Honeywell's model 1856 10-MHz facsimile recorder with Z-axis modulation, allows lower-weight and higher-reliability recorder instruments than previously possible.

Self-diagnostics for easier and lower-cost troubleshooting, and autocalibration to reduce instrument downtime, are two features that are showing up in greater numbers of instruments, with the microprocessor in some cases making them more practical. However, considerable differences of opinion exist among instrument designers as to the microprocessor's role here: some designers favor its use for such features; others argue that its additional cost is not warranted.

The level of instrument–operator interface simplicity more often depends on the type of instrument operator than the instrument's complexity. For example, instrument operators in the medical, petrochemical, and process-control fields, as well as those on the production line, have neither the time nor the technical skill to operate a myriad of complex controls, desiring instead the ultimate in control simplicity. The engineering/scientific user, on the other hand, requires some control over how an instrument is used, even though some level of control simplicity might be desirable.

An example of a totally operator-oriented instrument can be seen in Spectral Dynamics' model SD360 digital signal processor. The stand-alone hardwired FFT analyzer for industrial applications (measuring, analyzing, and controlling noise and vibration in machines and structures) combines the capabilities of two spectrum analyzers, a transfer function analyzer, analog signal conditioners, and a computer, and yet can be easily operated like a single instrument. A front-panel

[2] Hewlett-Packard's model 1740A oscilloscope atop the company's model 1607A logic-state analyzer functions as an alternate readout for data-domain information as well as conventional time-domain waveforms. The oscilloscope has a "gold-button" option for alternate-domain viewing.



joy-stick control, CRT display, and calibrated digital readouts of measured parameters afford the operator maximum control convenience at minimum skill.

New instrument concepts

The logic analyzer/recorder is an example of how conventional instruments such as oscilloscopes, limited in capability for measuring and analyzing digital-device circuits, have created new instrument concepts. Not that the oscilloscope is no longer needed. On the contrary, the combination of oscilloscope and logic-analyzer/recorder capabilities can often form a powerful measurement tool. Hewlett-Packard took this approach with its 1740A 100-MHz oscilloscope. Working in combination with the company's model 1607A logic-state analyzer (via a "gold button" option on the 1740A), alternate time-domain (waveforms) or data-domain (ones and zeros) information can be obtained on the 1740A's CRT by the push of a button (Fig. 2). The 1607A can also be used with the company's 1600A logic-state analyzer that includes a CRT for 32-bit-wide logic analysis.

A different combination approach is used by Tektronix with its LA501 logic analyzer plug-in (Fig. 3). Part of the company's TM500 line, it permits a portable oscilloscope/analyzer package to be assembled, small enough to fit into a suitcase, when used in combination with an SC502 oscilloscope plug-in and a DD501 delay plug-in. The LA501 differs from Hewlett-Packard's analyzers in that the former displays logic signals as binary waveforms vs. time (the instrument's real-time clock) or events (a clock signal derived from the system under test). The latter displays logic signals as a succession of vectors (ones and zeros on the screen) vs. events.

Advancements in timing logic analyzers continue, as can be seen in Biomation's model 851-D (Fig. 4) with a mixed-sweep-display mode—a mode analogous to that of an oscilloscope. This allows its user to view the instrument's memory contents on a CRT display in two segments: all digital data to the left of a movable cursor in normal fashion, and an expanded digital-data format to the right of the cursor. The expansion factor (up to 20×) is selectable from the front panel. The 851-D also has all the other features of earlier-model logic analyzers from Biomation.

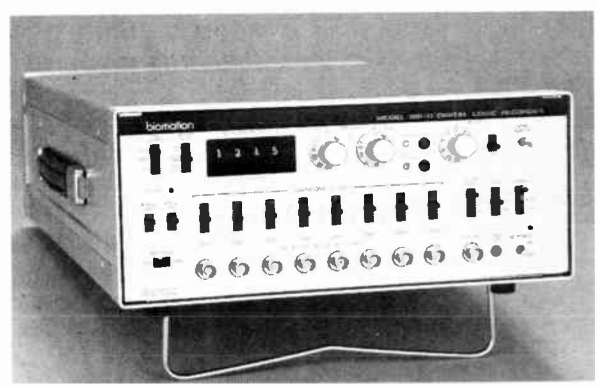
The proliferation of microprocessors of differing architectures and languages is also creating a need for universal instruments that can act as microprocessor development systems and provide software/hardware debugging.

The multifunction instrument

A recent trend has been to try to integrate several instruments into one case. This concept can also be seen in Tektronix's and Vu-Data's miniscopes, where a digital multimeter is housed in the former, and a digital multimeter and frequency counter in the latter. Even larger oscilloscopes—such as Hewlett-Packard's microprocessor-based model 1722A (the microprocessor's LED display essentially serves as a digital voltmeter) and Tektronix's models 464, 465, 466, and 475 with an add-on DM43 unit can be classified as multifunction instruments.

The most recent multifunction instrument is one from Philips—model PM2527. It is basically a digital multimeter that has true-rms and temperature-measurement capability within the same instrument case.

The multifunction approach can sometimes mean better performance. Wavetek, for example, came up with a low-cost solution to generally poor function-generator frequency stability, settability, and waveform spectral purity, by incorporating a frequency synthesizer into a function generator. In the synthesizer mode, the model 171 synthesizer/function generator (Fig. 5), covering 0.1 Hz to 2 MHz (sine, square, and triangle), features 0.005-percent frequency accuracy and 0.0001-percent/°C stability over 1.000 Hz to



[4] A mixed-sweep display mode, analogous to that of an oscilloscope, is possible with Biomation's latest logic analyzer, model 851-D. This mixed mode allows a user to expand and view the instrument's memory contents (on a CRT display) to the right of a movable cursor, while viewing data in normal fashion to the left of the cursor.

[3] A portable logic-analyzer/oscilloscope package. Tektronix's LA501 logic analyzer is combined with a digital delay unit and an oscilloscope for a measurement package small enough to fit under an airplane seat. The TM515 combination is part of Tektronix's TM500 line of instrument plug-ins.

[5] Wavetek's model 171 synthesizer/function generator is a low-cost solution to improving the performance of traditional function generators. It is basically a synthesizer with excellent function-generator performance levels.

1.9999 MHz. Resolution is 4½ digits in six decades. High spectral purity is assured with typical spurious signals of −70 dB to 20 kHz and −40 dB to 2 MHz. In the function-generator mode, the instrument can be manually swept with a front-panel dial or with an external voltage ramp.

Lower prices: a prime objective

One of the reasons for the multifunction instrument approach is to provide the user with more measurement capability per dollar—a prime design objective for some systems instruments as well.

The dictates of economics can often be seen in many highly competitive instrument types, such as general-purpose digital multimeters, service oscilloscopes, and function generators, where even higher performance is sometimes relegated to a lower price.

Emerging industrial and consumer service fields requiring low-cost instruments providing reasonably good performance are a major reason for economy. Hickok Electrical Instruments recognized this when it introduced its $165 model 440 curve tracer (for use with any oscilloscope) with capabilities often found in much more expensive curve tracers. The instrument is said to test diodes and bipolar and field-effect transistors, and has an "Insta-Beta" measurement mode that presents a single, full-range bipolar-transistor beta (I_c/I_b) curve for instant calculations of ac and dc betas, without interpolation. In the case of a FET, this feature shows the FET's entire transfer curve, including pinch-off voltage (V_p), fall-on current (I_{dss}), and transconductance (active portion) parameters.

It would be impossible to list all significant developments in low-cost instruments, but a few noteworthy recent ones in digital multimeters can be cited. These include Systron-Donner's model 7003 3½-digit multimeter with true-rms conversion for $295, Data Precision's model 3400 4½-digit systems multimeter at $795, Hewlett-Packard's model 3476A autoranging 3½-digit multimeter at $225, Keithley's model 168 3½-digit autoranging multimeter with a "Hi-Lo" ohms feature at $315, and B&K Dynascan's model 280 three-digit hand-held multimeter for $99.95.

New performance dimensions

Each time an instrument attains a new level of performance, still higher levels become necessary for new and advanced applications. This holds true for low-cost as well as expensive pieces of equipment.

Automatic microwave frequency measurements up to 24 GHz are possible with a development from Systron-Donner. The company's model 6054B counter (Fig. 6) is said to have a high degree of sensitivity (−30 dBm from 0.02 to 10 GHz, −25 dBm from 10 to 18 GHz, and −20 dBm from 18 to 24 GHz), and is extremely quiet (−65 dBm of output noise). The company credits the proprietary development of a new thin-film input sampler for the counter's advanced performance. It also cites the FLACTO (frequency lock automatic computing transfer oscillator) circuit technique employed, allowing the counter to accept complex signals, including those with high amounts of FM deviation.

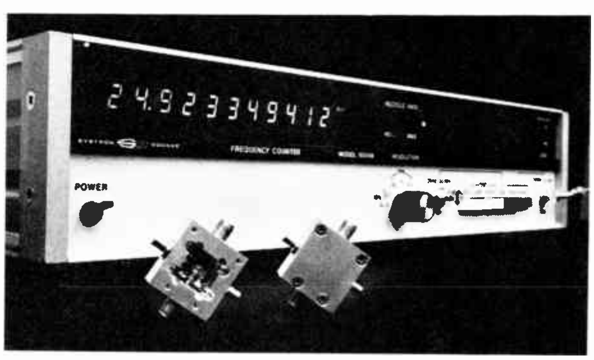
Higher measurement capability in an instrument such as a frequency counter often means looking at signals with greater noise contents and other disturbances. Often, the only practical measurement method under such circumstances is to use signal-averaging techniques, as is done in Hewlett-Packard's models 5328A and 5345A electronic frequency counters. The 5328A is a 512-MHz counter with 10-ps time-interval resolution, and the 5345A is a 500-MHz counter (18 GHz with plug-ins) with 2-ps resolution.

Instruments such as digital voltmeters are increasingly being designed for high degrees of resolution and accuracy, with some, such as Keithley's model 180, which is used for materials-research and differential-thermal-measurements applications, working at or very near noise levels. The 180 is a 4½-digit nanovoltmeter with 10-nV/digit resolution (100.00-μV range).

High noise rejection in a digital multimeter is becoming an increasing requirement, especially in a systems multimeter. An important development here has been California Instrument's Cimron DMM50 5½-digit multimeter with high noise rejection at high operating speeds. By combining the inherently high-noise-rejection advantages of integration logic with the high-speed advantages of successive-approximation logic, the multimeter's designers were able to provide an instrument with 60 dB of noise rejection at up to 20 readings per second. Up to 100-dB noise rejection is possible for low-speed operation (under two readings per second).

Another important voltmeter development has come from Ballantine Laboratories. The firm's model 3630A ac/dc true-rms digital voltmeter can measure the true-rms value of: ac voltages up to 1 MHz, from as low as 0.1 Hz; dc voltages; or mixtures of dc and ac voltages. Resolution of the 3630A, which also displays decibel quantities, is 0.01 dB on all ranges and 1 μV on the most sensitive range of 10 mV. ◆

[6] A proprietary thin-film sampler (foreground) is a major reason why Systron-Donner's model 6054B microwave counter can measure up to 24 GHz. The counter is reported to have a high degree of sensitivity, low noise, and high performance with complex signals including those with high amounts of FM deviation.



The author wishes to thank members of the engineering staffs of the following companies for helping in the preparation of this report: Dana Laboratories, Datel Systems, E-H Research, Hewlett-Packard (Colorado Springs, Loveland Instrument, and Santa Clara Divs.), Hickok Electrical Instruments, Honeywell Instruments Div., Interstate Electronics, Keithley Instruments, National Semiconductor (Transducer Group), Neff Instruments, Preston Scientific, Systron-Donner Instrument Div., Tektronix, Vu-Data, and Wavetek. Thanks also to representatives of the following companies who participated in a roundtable discussion on instrumentation: California Instruments, Doric, Ectron, Plessey Environmental Systems, Solitron, and Spectral Dynamics.

ANNOUNCING

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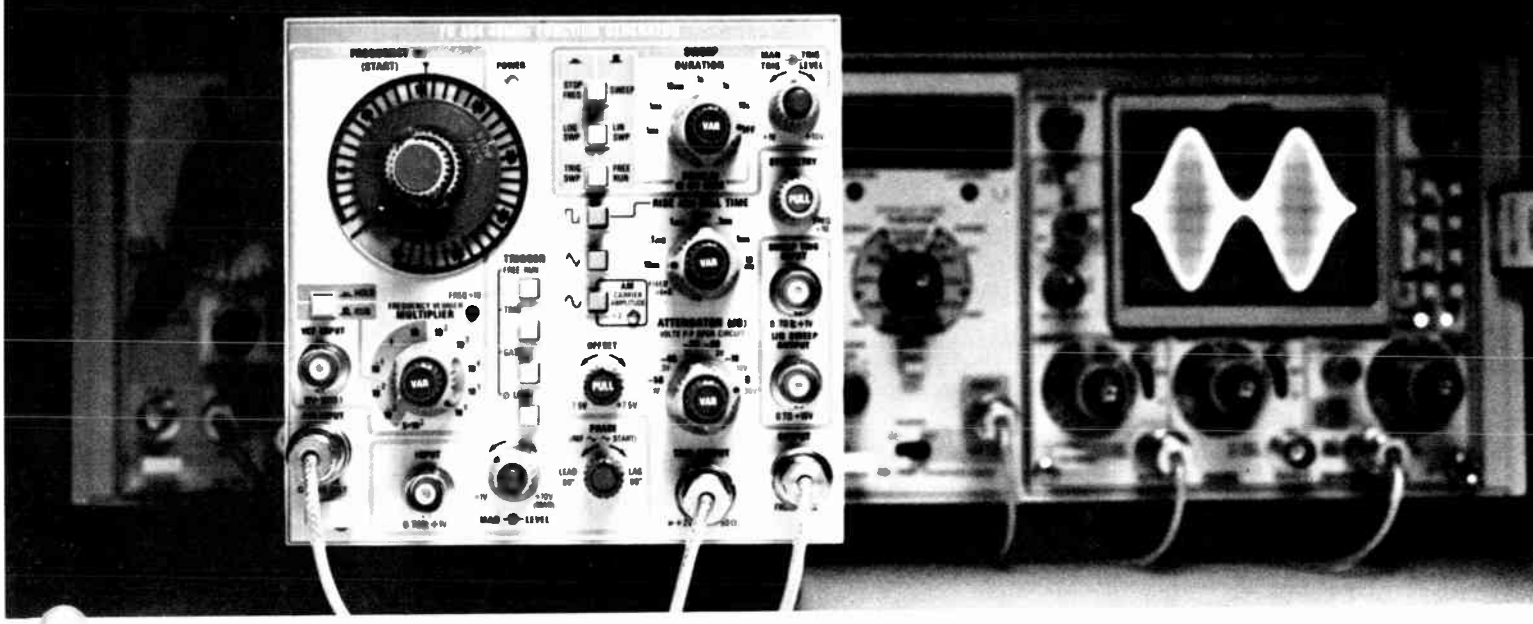

The TEKTRONIX FG 504

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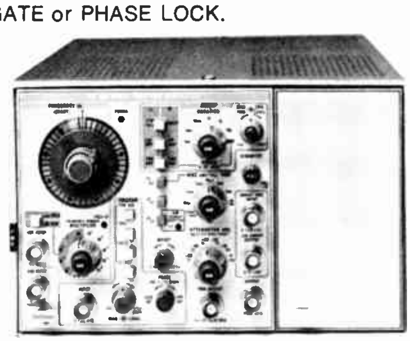

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Analyst to the analog world

Contemporary spectrum analyzers give even faint harmonics a 'high profile' by exploiting frequency domain display

Until relatively recently, spectrum analyzers were considered exotic test gear that could only be entrusted to a skilled engineer. Today, the picture is different. The modern spectrum analyzer is a highly versatile measuring instrument capable of performing many complex tests with relative ease. Equally at home on the production line or in the development laboratory, it can quite properly be classed with the oscilloscope as an everyday measurement tool. And from setting the response of a crystal filter to checking a mobile radio transmitter for spurious outputs, spectrum analyzer applications continue to grow—even reaching into the world of pulse code modulation.

To give those who are uninitiated in the aspects of the modern spectrum analyzer a feel for its versatility as an everyday tool, several typical applications will be described after a brief introduction to spectrum analyzer operation. The intent here is to trigger the reader's imagination, rather than to provide a definitive discussion of spectrum analyzers covering all existing applications and makes of equipment.

The analyzer's domain

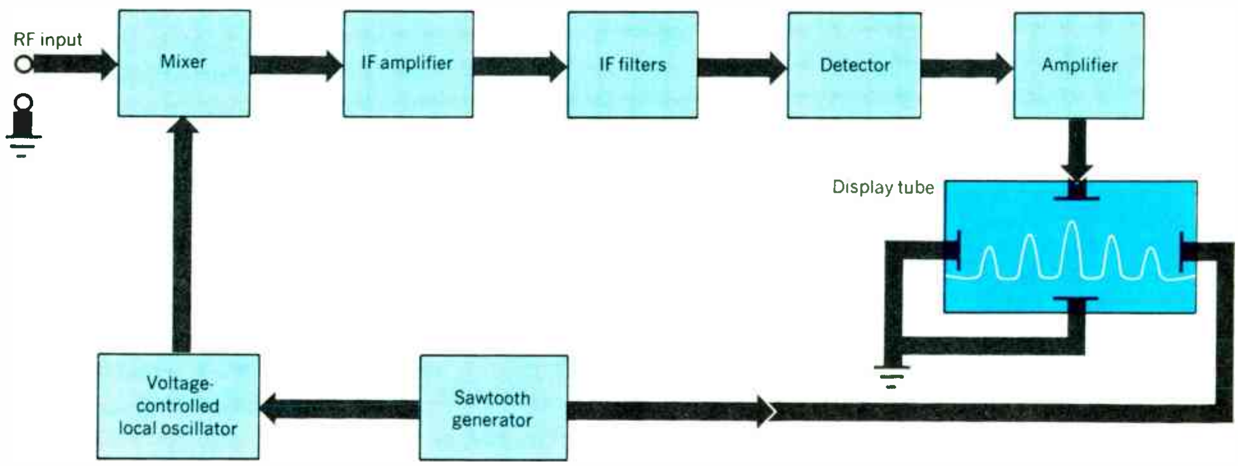
If a complex signal is fed to an oscilloscope, a presentation is given on the screen of the total amplitude of that signal against time. The oscilloscope is therefore said to be working in the "time domain." Although some basic frequency information can be calculated from an oscilloscope display, individual frequency components cannot be separately identified and examined. This factor is not important when working with logic circuits, but since most analog designs are commonly defined by their amplitude and frequency response, it is often more useful to have a presentation of amplitude against frequency—that is, a display in the "frequency domain." This is what the spectrum analyzer gives. The typical spectrum analyzer employs a swept-frequency technique that is the most suitable method of obtaining both the large bandwidth and wide dynamic range required for general-purpose engineering measurements.

The analyzer is essentially a superheterodyne receiver with a broadband input and a swept-frequency local oscillator (Fig. 1). The sawtooth voltage providing this sweep also provides the horizontal deflection for the display tube. As the local oscillator is swept, components of the input signal—which mix with the oscillator signal to produce the fixed intermediate frequency—will be amplified, detected, and applied to the display tube as vertical deflection signals. Thus, energy present at the analyzer's input is identified in frequency by its position along the horizontal axis, and in amplitude by its vertical deflection.

In practice, a modern spectrum analyzer is considerably more complex than Fig. 1 suggests. Several stages of intermediate frequency (IF) are required to give a wide input bandwidth, high resolution, and adequate rejection of spurious signals created by the mixing processes. The final IF must be low enough to permit narrow-bandwidth filters to be utilized to give good spectrum resolution. Use of a narrow resolving filter dictates a slow repetition rate of the sawtooth generator, if a distorted display is to be avoided. This slow sweep speed demands the use of display storage so that a complete image can be presented on the screen while

W. C. Greening Marconi Instruments

[1] Stripped to the bare essentials, a spectrum analyzer consists of a superheterodyne receiver swept by a voltage-controlled local oscillator. Sweep speed is determined by a sawtooth generator.



updating proceeds at a rate the resolving filter can handle accurately.

Range war: spurs vs. grass

Without careful design, there is a high probability that the spectrum analyzer will present misleading information. This may take the form of either spurious signals generated within the instrument or distortion and false presentation of the input information caused by ringing in the resolving filter. However, with modern design, the risk of such errors is now small.

Spurious signals appearing on the screen but not present at the input are caused by application to the first mixer of too high a signal level. As a result, a high level of intermodulation products is produced, and these appear on the display as if they were present in the input signal. In fact, spurious responses can be caused by too high a signal level at any component from the first mixer down through the conversion stages—up to and including the IF filters. Therefore, the choice of gains and losses through the conversion stages and the distortion performance of all the components are critical.

However, the less signal applied to the first mixer, the more gain required in the IF stages—and the more gain applied in the IFs, the higher the noise floor (grass) seen on the screen and the smaller the dynamic range available for making measurements. A compromise therefore must be reached between minimum spurious signals and minimum noise level.

If the operator has complete control over the RF and IF attenuators, a danger arises: in minimizing the noise floor, unwanted spurious signals may be unwittingly produced. To overcome this, the modern spectrum analyzer employs either a system of warning lights to tell the operator when incorrect results may be achieved, or else one set of front-panel controls is used to select the optimum combination of RF and IF attenuation for a particular input signal level. This solution can also be achieved with a hardwired logic program, provided that some limitation on the independent selection of RF and IF attenuation is acceptable.

To save time, the operator will wish to use as fast a sweep speed as possible. On the other hand, too fast a sweep causes ringing in the resolving filters and wrong answers. The situation is further complicated because varying sweep speeds may be used with the same resolving filters, depending on what frequency span the instrument is set to sweep. Again, the answer on a modern spectrum analyzer is found in lights that warn of possible error or a hardwired logic that automatically sets the correct sweep speed for the combination of filter bandwidth and sweep width selected.

It was development of the storage CRT that enabled the full potential of spectrum analyzers to be realized. At last, a slow sweep could be used to examine the spectrum, yet the picture would remain on the screen long enough to be seen in full detail. Now, a new generation of spectrum analyzers is entering the market employing, not a storage tube, but a digital store that gives truly infinite persistence and needs even fewer display controls than the conventional oscilloscope (in fact, the only display control to be found is the intensity control). A further advantage is that the store can be split into two interlaced halves, thus enabling two displays to be overlaid so that a direct comparison can be made between them. But tube technology has not stood still. Advanced-design storage CRTs can provide a similar capability.

Digital presentation of frequency is now included in many spectrum analyzers. This counter can show the center frequency of the display and also, on some analyzers, the frequency corresponding to the position of a movable electronic "cursor." The operator has confirmation that the displayed signal is the desired signal from a digital frequency readout, and the movable cursor enables accurate frequency measurement anywhere in the displayed spectra.

On-screen analysis

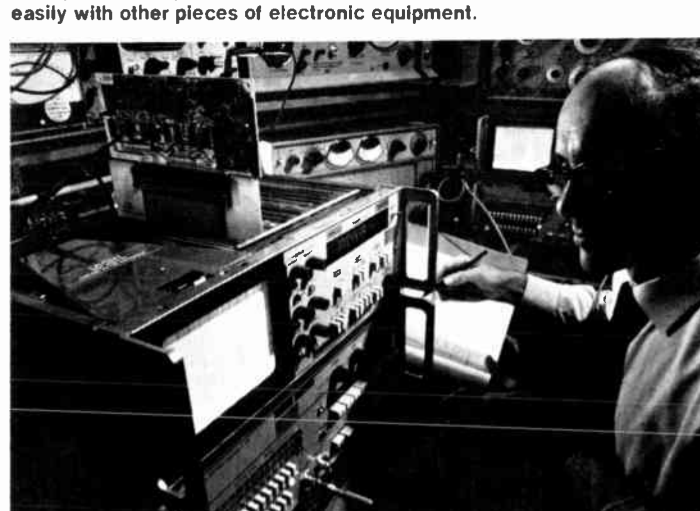
The measurement capability of spectrum analyzers is impressive. Frequencies from audio to microwaves can be examined using just one instrument mainframe and a series of plug-ins or extension units. A wide frequency band may be selected for observation, or a small "window" of a few hundred hertz (centered on any part of that band) may be displayed.

Resolving filters with 5-Hz bandwidths permit the detection of low-level spurs less than 50 Hz from a high-level signal. Modern logarithmic amplifiers can give the spectrum analyzer a display range well in excess of 80 dB, and, by expanding the vertical scale, amplitude resolutions down to 0.1 dB may be seen. However, it should be recognized that the display range (difference between the minimum and maximum signals that can be observed on the same CRT trace) is not necessarily equal to the dynamic range (difference between the signal and distortion products or noise floor for a given signal level).

The crowding of more and more transmissions into the available spectrum has caused Government authorities to place tighter and tighter specifications on the spurious output of transmitters. It is the examination of these spurious signals that forms the traditional use of spectrum analyzers. This includes the adjustment of single-sideband transmitters for maximum carrier supression and minimum intermodulation.

Examination of an amplitude-modulated carrier (Fig. 2) illustrates a common task well suited to the analyzer. From this display, a number of transmitter performance characteristics may be determined. The

Set up for testing, the modern spectrum analyzer interfaces easily with other pieces of electronic equipment.



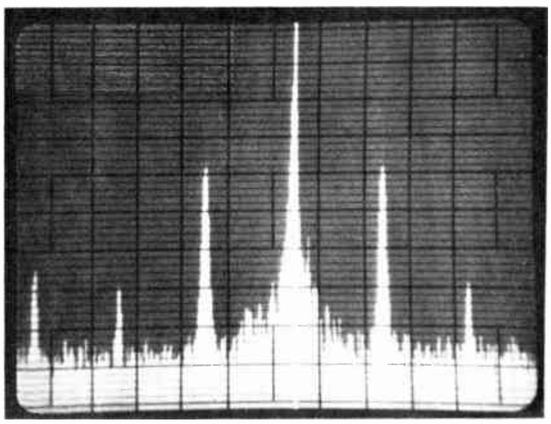
measured amplitude of the 200-Hz modulating sidebands quickly yields modulation depth. If the sidebands were only 6 dB down, we know the signal would be 100 percent modulated. In this example, the sidebands are 40 dB below the carrier, indicating a modulation depth of (40 − 6) dB = 34 dB below 100-percent modulation, or 2-percent modulation. It may also be seen that the second and third pair of sidebands (400 Hz and 600 Hz from the carrier) are a result of modulation distortion at levels 65 to 70 dB below the carrier. By expanding the frequency scale to observe the spectrum in more detail, any 50- to 60-Hz hum sidebands on the carrier may easily be detected.

Although both AM depth and frequency deviation are most readily measured with the use of a modulation meter, it is worth pointing out that the spectrum analyzer provides a highly accurate method of measuring both these parameters. Modulation depth is measured as already described, and frequency deviation by use of the Bessel zero technique. However, frequency deviation cannot be measured unless the observed spectrum contains a Bessel zero, so it is necessary for the observer to have control of the source so that the modulation index (frequency deviation and/or rate) can be adjusted for a Bessel zero. This technique is used primarily to calibrate modulated sources.

The usual method of finding frequency deviation for an uncontrolled source is to measure peak-to-peak excursions by examining the spectrum width (using a resolution bandwidth greater than the modulation rate), by using the slope of the IF filters as a discriminator, or by measuring the down-converted signal at one of the analyzer's IFs using a discriminator.

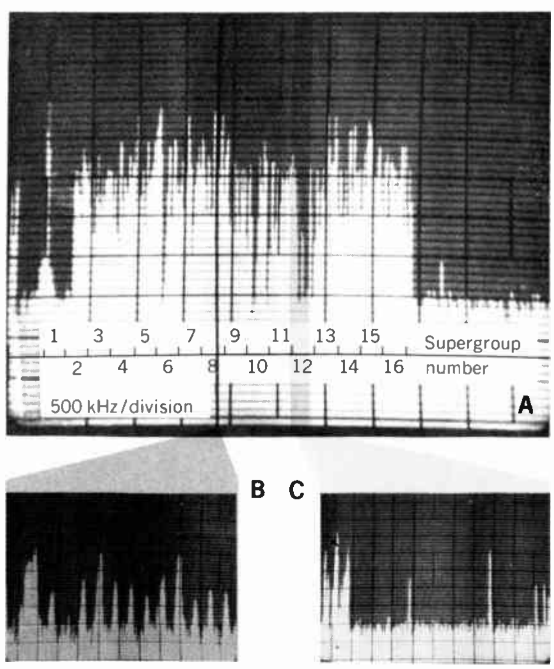
Similar techniques may be applied to measurements on frequency division multiplex (FDM) systems—for example, a 16-supergroup FDM baseband (960 channels) in traffic (Fig. 3A). Interpretation of the image is straightforward. The left-hand (dashed) graticule is the zero frequency point, and the signal on that line is the zero frequency marker with low-level, low-frequency noise around its base (the center of the screen is 2.5 MHz). The first traffic is seen at about 300 kHz; therefore, the first supergroup is missing (60 kHz–300 kHz). Other small gaps can be seen in the baseband structure, and another supergroup is missing at about 2.8 MHz; however, two discrete signals are visible within that supergroup space.

By switching the spectrum analyzer to a narrower sweep width and using a scan center frequency of 2880 kHz, the missing supergroup can be displayed in more detail (Fig. 3C). From this display, the missing supergroup can be identified as supergroup 12. If the spectrum analyzer used has a built-in counter, the frequency of the supergroup pilot can be measured. Expansion of another part of the same FDM baseband (Fig. 3B) shows the group and supergroup pilots in group 3, supergroup 8, of the 16-supergroup system. These pilots are adjacent to the fifth and ninth graticule lines, and traffic can be seen in one channel with carrier leaks in the quiet channels. And since the top line of the grati-

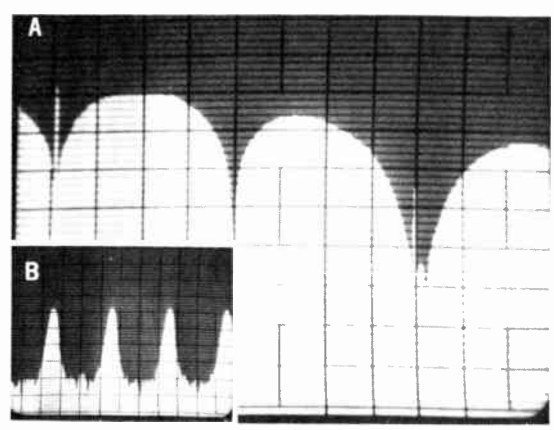


|2| This carrier is being amplitude modulated at 200 Hz. Modulation distortion at 400 Hz, 30 dB below the 200-Hz modulating sidebands, is clearly visible above the noise.

|3| Spectrum analysis of a 16-supergroup frequency division multiplex signal (A) uses narrow sweep width to resolve detail within the eighth supergroup (B) and twelfth supergroup (C). Pilots can be checked with the analyzer's counter.



|4| This test signal of 32-time-slot pulse code modulation (A) shows the main lobe of energy centered at 1.024 MHz and crystal clock breakthrough at 4.096 MHz. Set for narrow sweep, the analyzer resolves sidebands 62.5 Hz apart (B).



cule in Fig. 3B is calibrated to a power level of −36 dBm, the group pilot level can be read as −76 dBm.

As just illustrated, the spectrum analyzer can be used to make measurements normally obtained with a selective level measuring set (SLMS), but the data have been gathered much more rapidly, and the pictorial view of the baseband spectrum presented is considerably easier to interpret than a series of single measurements. A spectrum analyzer can be of great help for overall observation, but it cannot replace a SLMS for accuracy because the SLMS: (1) has a 3.1-kHz bandwidth IF, defined for telecommunications measurements; (2) reads in rms or weighted power as defined for the bandwidth; and (3) has much better amplitude accuracy than a spectrum analyzer.

Pulse code modulation (PCM) transmissions are being widely introduced as an alternative to FDM, and spectrum analyzers are being applied to measurements of these systems. The analyzer display of Fig. 4A shows a typical test signal used for 32-time-slot PCM. The signal is a pseudo-random binary sequence of length $(2^{15} - 1)$ at a 2.048-Mb rate, AMI coded, and the display shows the main lobe of energy centered at 1.024 MHz (half the bit rate). Crystal clock breakthrough can be seen at 4.096 MHz. It can be anticipated that sidebands will be present in the above signal at a spacing equal to bit rate divided by sequence length, or, for this example, 62.5 Hz. Setting the analyzer display at 20 Hz/division with a 5-Hz filter (Fig. 4B) resolves these sidebands. Spectrum analyzers are found to be of particular value in the installation and acceptance testing of PCM systems when it is necessary to measure the inband and out-of-band signal responses.

Tracking down a filter bandpass

A common feature of spectrum analyzers, either as an option or a standard, is a tracking generator. The frequency of this swept-signal generator is maintained, within close tolerances, at the same frequency to which the spectrum analyzer input is tuned at any given instant, and its output is leveled, typically to within 1 dB. This combination of synchronous analyzer and generator forms a powerful system for measuring frequency response over a wide dynamic range.

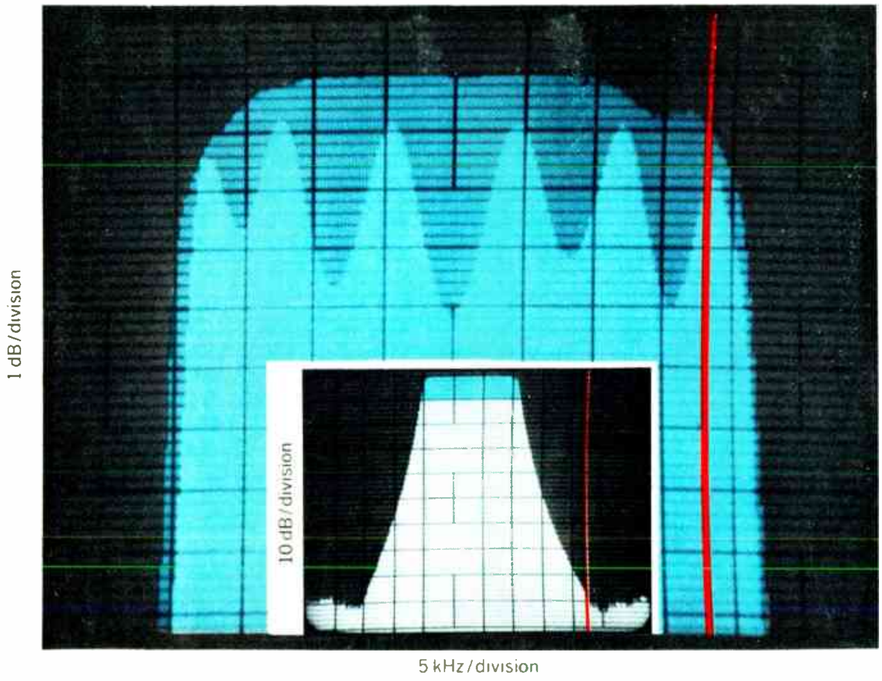
The measured response of a crystal bandpass filter (Fig. 5) serves as a good example. Wide dynamic range of the analyzer permits observation of 90-dB out-of-band rejection. Clearly, measurement of the filter bandwidth at, say, 60 dB down on the skirt would be equally easy. The inclusion of a frequency counter within the spectrum analyzer permits far more accurate frequency measurements than are possible from the markers of a conventional sweep generator.

Switching the spectrum analyzer to a vertical scale of 1 dB/division and expanding the frequency scales slightly (Fig. 5) allow the top portion of the bandpass to be examined in detail.

A digital store can be split in two halves, the image from one half being overlaid on the image in the other half. Figure 5 shows the same bandpass filter with an incorrectly set loading coil (ripple response) and a flat passband after proper adjustment. The counter (vertical cursor) can be used to measure either the 1-dB or 3-dB bandwidth with a high degree of resolution. This digital dual-store mode is a very powerful tool for setting frequency responses. With a reference response held in one half of the store, the swept response of the item under test is displayed as an overlaid image, and the test object is adjusted until the live image is coincident with the reference.

As well as offering a wider dynamic range than a conventional sweep generator system, the spectrum analyzer/tracking generator combination has the considerable advantage of being a tuned system. However, inherent lack of stability (spurious or residual FM) on the sweep generator's output limits the minimum sweep width that can be used successfully.

A high-resolution spectrum analyzer with a narrow resolution bandwidth (5 Hz) is forced to have residual FM less than the width of the narrowest resolution



[5] The complete bandpass of a crystal filter (center insert) can be examined in greater detail by switching the analyzer to 1 dB/division and expanding the frequency scale. Digital storage allows comparison of desired (flat) response with an improperly loaded unit needing final tuning and adjustment.

bandwidth in order for that narrowest resolving filter to be useful in resolving signals. The low residual FM is usually obtained by employing phase-locked and/or frequency-synthesized local oscillators not commonly used in sweep generators. If the tracking generator output signal is then reconstructed from these local oscillators, the result is a highly stable, sweepable source. This source can then be used to a minimum sweep width of roughly ten times the analyzer's residual FM.

Using the sweep generator with a wide-band detector poses another potential problem. The wide-band detector is less sensitive than the spectrum analyzer, and this limits dynamic range. If a preamplifier is placed in front of the detector to improve sensitivity, the dynamic range is still limited because the detector will detect the noise over its entire bandwidth. A spectrum analyzer/tracking generator system overcomes this by using a narrow-band detector (the analyzer's resolving filter), which automatically tracks the desired signal.

A spectrum analyzer/tracking generator system is not confined to filter measurements, and may be used whenever it is desired to measure or adjust an amplitude/frequency response of devices whose input and output frequencies are the same. Measurements on amplifiers, modulators, detectors, and cable equalizers all come to mind. Frequency converters and mixers cannot be measured unless additional components are used to reconvert the output frequency to the input frequency.

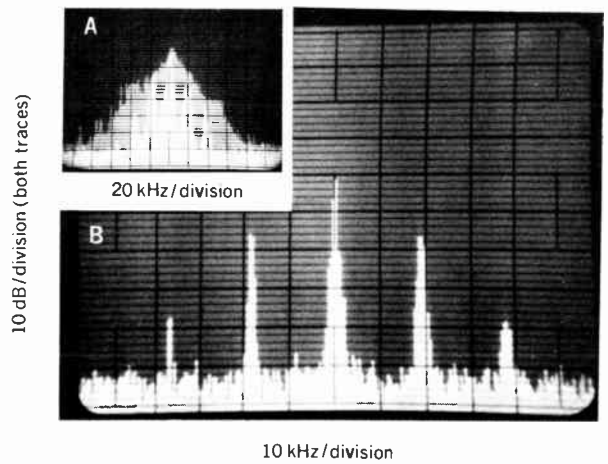
Spectrum security

A good spectrum analyzer is, of course, an excellent receiver. Its analytical ability makes it an excellent off-air measurement device as well as an ideal instrument for spectrum surveillance. Figure 6B shows the signal received from an FM broadcast station transmitting at 93.5 MHz with the spectrum analyzer used in a single sweep mode. The sweep took place during a quiet passage on the transmitter and the 19-kHz stereo pilot tones can easily be seen.

The same transmitter can also be examined with a different frequency resolution by using an analyzer with a split digital store (Fig. 6A). In one half of the store the transmitter's output spectrum is again captured during a quiet passage, while the other half of the store demonstrates how easy it is to measure occupied bandwidth in terms of decibels down from the carrier. A peak memory mode on the spectrum analyzer was used to find the total spectrum (170 kHz) used by the transmitter over a 15-minute period.

When fed from a good antenna, the spectrum analyzer can become a very powerful tool for spectrum surveillance—but not without some modification. Typical analyzer design optimizes dynamic range, and a poor noise figure (20 to 30 dB) results. High sensitivity is obtained by using a narrow resolution bandwidth. Therefore, spectrum surveillance with a sensitivity of a few nanovolts is possible only with a narrow resolution bandwidth and results in either very narrow frequency spans or very long sweep times. Preamplifiers are needed for most spectrum surveillance work.

[6] Monitored for 15 minutes using digital storage, this FM broadcast occupies about 170 kHz (A). The 19-kHz stereo pilot remains when the audio modulation is absent (B).



Frequencies found and tagged

Many of the examples discussed have demonstrated the frequency-measurement capability of the spectrum analyzer. A digital frequency counter is an accurate tool for measuring "clean" inputs, but as soon as other frequency components of comparable level are added to the signal, frequency counter capability is lost. However, a spectrum analyzer will separate the frequency components of a modulated signal, permitting measurement of any one of them.

It is no longer necessary to place the signal whose frequency is to be measured precisely in the center of the spectrum analyzer display. Simply by using the built-in frequency counter to display the frequency corresponding to the position of a movable cursor, the frequency of any displayed signal component can be found easily. The narrow bandwidths (as low as 5 Hz) and excellent shape factors of the resolving filters available in modern instruments allow frequency measurement with a resolution of a few hertz, even at frequencies above 100 MHz. And there are other techniques, such as using the analyzer's tracking generator in a mode where the input frequency of the signal under measurement is restored and counted.

The spectrum analyzer is a very powerful swept system. As a receiver, its frequency-measurement capability extends to those signals that, because of modulation, would confuse an ordinary frequency counter, and it can be used in place of a selective level-measuring set in a wide number of applications. Its ease of operation enables it to be changed swiftly from one measurement technique to another, whether it be operated by a skilled engineer or a test technician. ◆

W. C. Greening is the export regional manager for Marconi Instruments Ltd., responsible for sales into Western Europe, a position he has held since 1972. During this time, he has been deeply involved in the applications of Marconi's new range of signal generators, spectrum analyzers, and white-noise test sets. Mr. Greening first joined Marconi Instruments in 1967, after receiving the bachelor-of-science degree in physics at the University of Bristol. In 1969, he transferred to the U.K. sales team as sales engineer for part of London and the surrounding counties and, although responsible for selling a range of products, Mr. Greening again found that the bulk of his work involved RF measurements.

'Super' scopes

The oscilloscope, traditional workhorse of the EE, is coping with many new applications, including logic analysis

Through most of the history of electrical and electronics engineering, the oscilloscope has been the single most versatile measurement instrument in the designer's arsenal of test and measuring equipment. While its basic functions have remained the same—to acquire, display, and permit analysis of time-related signals—despite the shift from an analog to a largely digital environment, the oscilloscope has taken on new levels of sophistication and versatility, thanks to IC-device advancements and circuit-design innovations. Modern oscilloscopes provide their users with more measurement power per dollar than ever before.

New capabilities

The first oscilloscopes provided mostly qualitative information limited to a few kHz of frequency and a few volts of signal amplitude. Further, they were generally restricted to the laboratory environment and required a lot of guesswork. Newer versions allow quick and very accurate quantitative as well as qualitative signal analysis, over bandwidths hundreds of MHz wide, and down to microvolts of signal levels. Some have been designed for portable service applications. And the sheer power of performance available in systems oscilloscopes to process data relegates the CRT display to an almost ancillary role. In fact, with some systems oscilloscopes, the operator has nearly been removed from the measurement loop.

The continuing advancements in electronics technology have created a need for oscilloscopes that can perform many new types of measurements. Spectrum and logic analysis, sampling, digital conversion, and time-interval measurements are just a few. Oscilloscopes have therefore branched out into several distinct configurations, each designed to meet a particular group of these measurement needs.

One of the earliest efforts to expand the oscilloscope's measurement capability was the concept of a mainframe oscilloscope with various plug-ins, each designed for a specific measurement need. Tektronix's series 5000 and 7000 and Hewlett-Packard's series 180 oscilloscopes are examples.

The plug-in configuration provides an oscilloscope user with the greatest measurement versatility. Not only can traditional measurement tasks be accommodated, but new plug-ins can be used to convert the oscilloscope into a spectrum analyzer, logic analyzer, sampling oscilloscope, time-domain reflectometer, etc. Tektronix's series 7000 oscilloscopes accept analog and digital plug-ins covering applications from an alphanumeric text generator to an optical-sensing spectrometer. Hewlett-Packard's series 180 oscilloscopes accept spectrum- and logic-analyzer plug-ins.

Leon Orchard, William Peek Tektronix, Inc.

In some cases, the oscilloscope can perform two functions simultaneously, as when displaying a signal in both the time and frequency domains. A variety of vertical-amplifier, time-base, and special-purpose plug-ins make possible a large number of combinations and permutations to match the oscilloscope to the measurement requirement.

The new look of oscilloscopes

Newer oscilloscopes with digital multimeters in the same package (or on top of the oscilloscope's case) have recently become available. A particularly useful feature of most oscilloscope–multimeter combinations is the ability of the digital multimeter to provide a digital reading of time between events. The growing number of digital IC devices has made timing measurements increasingly important, and the accuracy provided by the digital readout is often essential. Accuracy specifications can be within 1 percent.

In addition to the conventional multimeter functions, these new instruments also offer several other measurement capabilities. Tektronix's DM43 offers temperature-measurement capability. On Vu-Data's model PS915/975, a frequency counter is included.

Digital multimeter functions for oscilloscopes are provided by several methods. On some instruments, including Tektronix's model DM43, Hewlett-Packard's model 1722A (Fig. 1), and Vu-Data's PS915/975, a separate LED display is used, and both the CRT display and the digital values are read in tandem. Tektronix also offers on-screen digital readout in its series 5000 and 7000 oscilloscopes. In its miniscope models, the CRT is used alternately for both analog and digital display functions.

These oscilloscopes cannot, as yet, actually make many new types of measurement, but they do offer significant increases in accuracy, speed, and reliability—by decreasing the chance of operator error. Their most immediate impact has been on time-interval measurements, providing more accuracy.

Portable oscilloscopes

The explosive growth of the computer and telecommunications markets created the need for true oscilloscope portability—an oscilloscope that can be easily carried into the field and operated from a battery. Oscilloscope weight and size reductions have become so pronounced that, on some high-frequency models, the weight of the batteries has become significant. And a new class of portables has emerged within the last two to three years—miniscopes. These tiny oscilloscopes can fit into a briefcase. Some are even hand-held versions (Fig. 2). The cost–performance ratio is generally high on the better miniature oscilloscopes and performance and battery-life parameters are limited by availability of small CRTs with low power drain.

While not a new capability itself, the extent to which portable oscilloscopes are extending their range of performance is a significant development. Even though a portable oscilloscope can never match the versatility of a laboratory plug-in type, many portables are in fact showing up in the laboratory, due to their ease of use, smaller size, and lower cost/performance. For example, Tektronix's models 485 with a 350-MHz bandwidth and 466 with fast-transfer storage, and Hewlett-Packard's model 1722A with a built-in microprocessor, are portable instruments that are also used in the laboratory.

Lower-frequency service oscilloscopes

Another area of rapid oscilloscope change has been in the low-frequency (bandwidths of about 50 MHz or less) oscilloscope field. Designed for service, production, and school use, as well as medical, mechanical, and other low-frequency R&D applications, these oscilloscopes are available in a range of portability, from hand-held units to models for bench use that also have a handle on top. In the last few years, increasing sophistication has pervaded the design of these oscilloscopes, with some including features, such as dual trace and triggered sweep, that previously could only be found on more costly laboratory oscilloscopes. Examples include Tektronix's T900 line of storage and nonstorage models with 10- to 35-MHz bandwidths at comparatively low prices, and Ballantine Laboratories' modestly priced 40-MHz model 1040A with performance found in more expensive units.

Special models are also increasingly available. Oscilloscopes aimed at TV service often include line and sweep triggering, and some have vector displays as well. Telequipment, Ballantine Laboratories, Heath, RCA, B&K Dynascan, Leader Instruments, Sencore, Systems Electronics, and Hickok Electrical Instruments, among others, are strong in this field. For industrial service, double-insulated oscilloscopes that can be floated on moderately high line voltages are available to make trouble-shooting motor controllers much easier.

Accessory recorders are also available. These can, among other feats, effectively transform low-frequency oscilloscopes into storage oscilloscopes. Ballantine Laboratories offers a 100-kHz signal recorder that captures transient or repetitive signals on a small loop of magnetic tape, running at a constant speed of 20 ms/revolution past a record-playback head, with recording being achieved by an FM magnetic recording technique. Triggering circuits with controllable delays switch the unit from the record to the playback mode when trigger conditions set by the user are reached. The continuously rotating loop then plays back the captured signal repetitively into any real-time oscilloscope for viewing and analysis or can be fed to power or spectrum analyzers, auto correlators, or other analytical devices, as needed. Both pre- and post-trigger information can be presented. Tapes can be stored and played back at any later date if desired. Such recorders are available at modest prices.

Optimation provides a digital means to perform the same function by sampling the signal and storing the sampled level in solid-state memory. Playback is achieved by strobing the memory. Resolution of the stored signal is dependent on the number of bits of memory in the system, and cost can be several times higher than the FM analog magnetic recording technique. No permanent storage is available, but the digital accessory recorders lend themselves to flexibility in handling long or short transients since strobe-in and strobe-out rates can be adjusted for different record and playback timing intervals.

Digital oscilloscopes for digital tasks

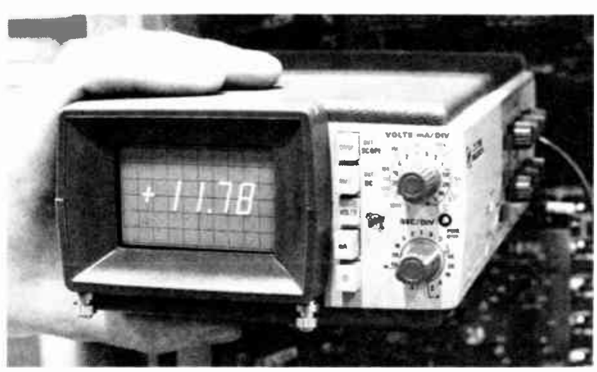
Instrument intelligence, obviously a significant step, has taken two forms so far in oscilloscope design. The most striking has been the appearance of several digital oscilloscopes, but no less significant has been the integration of computational circuits within the interfacing of the more traditional analog designs.

Of the digital oscilloscopes, two principal variants are available. One is the keyboard-centered type, where various calculator-like controls enable the user to present common displays and make calculations. Norland Instruments and Nicolet Instrument have both brought out units of this type.

The second digital oscilloscope type is the truly programmable unit. This feature is available in the Tektronix Digital Processing Oscilloscope System, as well as Norland's model NI 2001. Taking instruction from a stored sequence, these units literally contain small computers or interfaces, and can therefore repeat the

[1] The LED display on Hewlett-Packard's model 1722A microprocessor-based oscilloscope indicates the period of the waveform under observation. The use of a microprocessor also allows highly accurate display of analog-trace voltage magnitude, the time interval between traces, and signal frequency, as well as a number of other parameters.

[2] Small enough to fit into a briefcase, one of Tektronix's miniscopes can even be handheld. The oscilloscope presents alternate analog and digital display information on its CRT.



same measurement endlessly without tiring, or branch to new sequences depending on parameter value.

While not presently capable of matching analog oscilloscope performance in a number of areas, digital oscilloscopes have the ability to store a signal, expand a portion of the display, invert it, and compute the maximum and average values. Some can perform powerful mathematical operations as well, such as fast Fourier transforms. Another outstanding feature offered by some models is the ability to display events occurring before and after the trigger signal.

Adding processing power to analog oscilloscopes will probably affect increasing numbers of users, at least in the short run. So far, both microprocessor and hard-wired models offer only a limited number of fixed functions, but the start looks promising.

Although not necessarily programmable, the combining of both digital and analog plug-ins in laboratory oscilloscopes has also produced a new dimension in performance. Such items as A/D converters, counters, and sample-and-hold amplifiers provide the oscilloscope with both ease of operation and a clear, fast display. The two types of plug-ins, working together, often present advantages not otherwise possible. The most advanced of such systems currently is Tektronix's 7000 series, which also offers on-screen digital readout of the measurement results.

Delayed sweep improves triggering

A long-standing problem in oscilloscope operation has been the display, at sufficiently high sweep speeds, of a signal that does not have (or is not immediately preceded by) a recognizable triggering characteristic—e.g., the details of a single pulse in a long train of positive logic pulses (Fig. 3). Since all the pulses look alike to the triggering circuits, it is impossible to trigger on any particular one. A marker (such as a negative or higher-amplitude pulse) preceding the train would serve as a trigger for displaying the pulse train. However, if the pulse of interest occurs far down the line after the trigger signal, only a relatively slow sweep speed will capture it, making detailed examination impossible.

The first solution to this problem was the delayed-sweep technique, which employs two sweep generators. The first generator, initiated by the trigger signal, generates the "A" or delaying sweep. The same circuits also supply a ramp to a voltage comparator whose other input is a dc threshold voltage, controlled by a "delay time" potentiometer. When the sweep and

Performance maximums

Traditionally, the most significant parameters of an oscilloscope's performance have been bandwidth and rise time, sweep speed, accuracy (both vertical and horizontal), and, since the appearance of the storage oscilloscope, maximum stored writing speed.

Maximum performance values are usually (but not always) found in laboratory oscilloscopes. Those who use them—scientists, R&D groups, advanced-circuit designers, etc.,—are the principal beneficiaries, and create a constant demand for faster and more accurate instruments.

The best gain/bandwidth available in a real-time oscilloscope (Tektronix model 7904) is 500 MHz at 10 mV/division (roughly 1 cm/division) or 1 GHz with direct access to the CRT (at about 4 V/division). A dual-beam oscilloscope (Tektronix model 7844) offering 400 MHz at 10 mV or 1 GHz with direct access (at about 4 V/division) was also announced in the past year. In sampling oscilloscopes, equivalent bandwidths of 18 GHz are offered (Hewlett-Packard's model 1811 with the 1430C sampling head).

Rise time in real-time oscilloscopes is closely related to bandwidth. The rule of thumb usually applied is T_r = 0.35/BW (this relationship assumes a Gaussian response that is uncharacteristic of the modern oscilloscope). Depending on its intended use, an oscilloscope's response can be optimized for either bandwidth or rise time. Thus, a 500-MHz oscilloscope offers a nominal rise time of 700 ps at 10 mV/division or 350 ps by direct access to the CRT.

Sampling oscilloscopes offer the fastest equivalent rise times and widest equivalent bandwidths, but are useful only with repetitive signals. Under the proper conditions, plug-in sampling oscilloscopes can achieve rise times as fast as 20 ps, or bandwidths of 18 GHz.

The modern portable oscilloscope runs a surprisingly close second to the more sophisticated laboratory instruments where bandwidth is concerned. Indeed, only a few years ago, the state-of-the-art oscilloscope offered considerably less than the 350-MHz bandwidth at 5-mV/division performance that is available in today's fastest portables (Tektronix's 485). The associated 1-ns rise time is highly desirable in trouble-shooting fast digital equipment—one of its primary applications.

Although it would be a contradiction to refer to the upper-frequency limits of low-frequency oscilloscopes, it should be kept in mind that bandwidth is useful only when it can be achieved without undue sacrifice of gain. In this respect, the ability of some low-frequency oscilloscopes to display a 1-MHz signal at 10 μV/division is almost as remarkable as the achievements of the laboratory oscilloscope.

Obviously, wider bandwidth in oscilloscopes would be useless in many applications without a corresponding increase in sweep speeds. It follows that the oscilloscope offering the widest bandwidth should also offer the fastest sweep speed. The 500-MHz oscilloscope referred to earlier offers a calibrated sweep speed of 0.5 ns/division, permitting the full-screen display of only 2.5 cycles of a 500-MHz signal.

The fastest portable oscilloscope available today (350 MHz) provides a maximum sweep speed of 1 ns/division.

In the low-frequency group, almost all instruments incorporate time bases of sufficient speed to present full-screen displays of one cycle or less at their upper bandwidth limits.

Perhaps the most startling advance in oscilloscope technology in the past year or two has taken place in the direct-view storage oscilloscope. This highly useful "memory" oscilloscope has traditionally been limited by its "stored writing speed"—i.e., the highest deflection velocity that can be imparted to the CRT's electron beam while still producing a visible trace on the storage screen. Development of the fast-transfer storage technique, however, has made it possible to produce a direct-view laboratory oscilloscope with a maximum stored writing speed of 1000 cm/μs. But the fastest stored writing speed, is offered by a portable oscilloscope—Tektronix's model 466 with a stored writing speed of 1350 cm/μs! This instrument can store sine wave signals up to 100 MHz in frequency.

delay-time voltages coincide, a second trigger is generated to start the delayed sweep, whose speed can be independently adjusted of the delaying sweep. The event displayed by the faster delayed sweep can thus be examined in full-screen detail. And, by using the delayed-sweep gate to produce an intensified zone on the delaying sweep, time-interval measurements can be made with much greater resolution than possible from graticule markings, simply by alternately positioning the start of the intensified zone at the beginning and end of the interval, then subtracting readings from the delay-time vernier control.

More recent refinements include mixed-sweep and dual-delay concepts. The former displays the delayed and delaying sweeps on one baseline, eliminating the expense of having sweep-switching circuits. The latter requires three sweep generators—one for the delaying sweep and one for each of the delayed sweeps. Each of the delayed-sweep generators also supplies an intensified marker as described above. Since both delays are triggered simultaneously, any nonlinearities in the delaying sweep affect them equally. The delay-time threshold voltages control circuits that generate a highly accurate digital readout of the time-interval measurement. Dual delay with digital readout of the time interval is offered in Tektronix (7000 series) and Hewlett-Packard (model 1722A) oscilloscopes.

Digital delay for more stable displays

Analog delay techniques, such as those described above, have certain limitations for analysis of digital logic pulse trains. In the example cited, it was assumed that the train was preceded by a recognizable trigger pulse, and that the period between trigger and pulse under examination was constant. Neither assumption is valid for all digital logic applications. For example, the period between a disk sector pulse and, say, the 999th pulse in the following logic train may vary minutely but significantly, due to mechanical aberrations in the disk drive mechanism. The delay interval, on the other hand, is virtually constant. The resulting time jitter causes a blurred delayed-sweep display that no adjustment of controls can correct. In one solution, a digital-delay or delay-by-events counter (Fig. 3) counts events after the trigger, until a preset threshold count (adjustable from the front panel) is reached, and then generates a trigger pulse for the oscilloscope. Because the time interval between the trigger and the pulse under examination is so short, variations in the disk's angular velocity have no appreciable effect on the display.

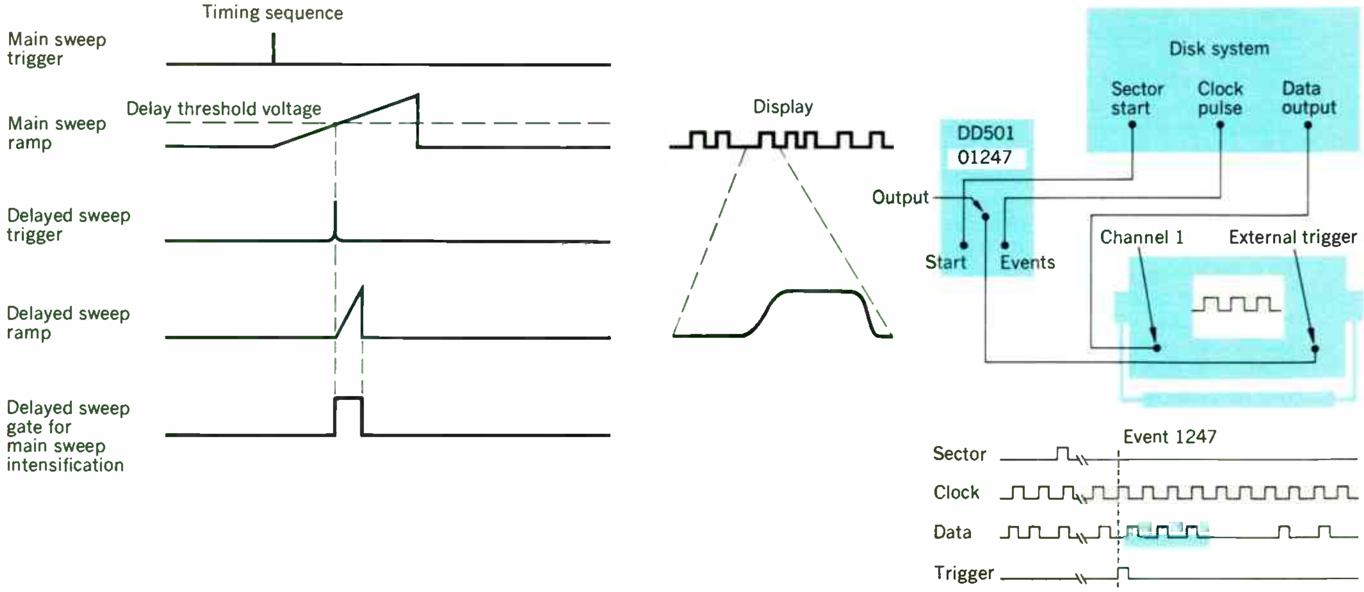
Where there is no satisfactory trigger pulse to start a delay-by-events counter, a word recognizer is required; it monitors logic outputs and generates an oscilloscope trigger when a preset logic combination occurs. Both serial and parallel word recognizers, as well as digital-delay units, are available as oscilloscope plug-ins or as auxiliary units.

Brighter and better CRTs

Since the oscilloscope is a display as well as a measurement device, a good share of the advances in oscilloscope design have been devoted to the CRT and its associated circuitry. Displays are larger and brighter, not only in laboratory but also in portable oscilloscopes and in some of the newer low-frequency lines. Photographic writing speeds as high as 6 cm/ns can now be achieved with an 8- by 10-cm CRT, and without prefogging. Parallax-free, internal graticules have become more the rule than the exception in all but the lowest-priced models. A recent innovation in oscilloscopes is autofocus control. Once the desired intensity is selected and the beam properly focused, further changes in intensity can be made without corresponding focus adjustments. Separate intensity controls for both A and B sweeps are provided in these same models, and for character-readout brightness where a CRT digital readout is featured.

The CRT digital readout is, in itself, a fairly recent and, to many, an exciting advance in human engineer-

[3] Older analog delay techniques (left) are insufficient for requirements of digital design and trouble-shooting, such as trouble-shooting the output of a computer storage disk. Newer digital delay techniques (right) using the Tektronix DD501 plug-in (part of the company's TM500 line) allow a stable display of information, no matter how far down the pulse train an event occurs.



ing. As oscilloscopes have grown in sophistication, the number of dials, switches, and controls has multiplied correspondingly. The mental arithmetic required to interpret a display correctly is sometimes beyond the capacity of an inexperienced (or overtired) operator. In any event, it consumes valuable time. In recognition of this problem, most manufacturers of digital oscilloscopes have provided systems that spell out on the CRT screen the significant display parameters in alphanumeric characters. In those instruments that accept digital plug-ins, the measurement is also presented in clear, accurate, digital terms along with the corresponding analog waveform. This not only eliminates most human error and facilitates quick measurements, but when the display is photographed, all significant data are permanently recorded for future analysis.

No discussion of oscilloscope display advances would be complete without mention of the new fast (mesh) transfer-storage CRT. Combining many of the techniques used in bistable and variable-persistence mesh-storage CRTs, the fast transfer tube, made by Tektronix, first captures the trace image on a fast mesh, and then transfers it to a long-retention mesh from which it is finally transferred to the phosphor surface. The result is a storage tube that can achieve writing speeds up to 1350 cm/μs—sufficient to display and store signals up to 100 MHz. Many industry sources predict that the gap between maximum bandwidth and maximum stored writing speed will close even further in the not-too-distant future.

The importance of human engineering

Not the least important contributions to the development of modern oscilloscopes have been made in the field of human engineering. Actually, any contribution that makes an instrument easier to use, whether through reduction in the training time required for its efficient use, or by simply making it easier to move from one location to another, is good human engineering. And under this definition, the most prominent example is the impressive reduction in size and weight effected in the past ten years. This reduction is exemplified not only by the miniscopes (previously discussed) that easily fit into a technicians's tool kit, but can also be seen in the most sophisticated laboratory oscilloscopes. The transition from vacuum-tube to transistor to integrated-circuit technologies has played a major part in this evolution. The oscilloscope industry has also made its own sizable contributions.

As the volume required for internal hardware continued to diminish, the front-panel area needed for merely the indispensable controls would have halted further miniaturization very early. However, manufacturers have met this challenge by developing ingenious new switches. These include push-button switches that can be spaced only a fraction of an inch apart, some of which light up to show their position; miniature low-torque barrel switches with multiple cams that operate contacts mounted on printed-circuit boards; and optoelectronic switches that give the designer freedom to locate his control wherever convenience dictates, without regard to the switch's location.

Systems of color coding that link common control functions for quicker identification are in common use. Front-panel limitations or size reduction have only been partially alleviated, however, and this challenge still remains an instrument designer's headache.

New applications

Wherever electronic technology invades a new field, oscilloscopes must be there to help design the product and service it.

Digital electronics is, of course, the most prominent new area. Whether found in computers, or in products like kitchen ranges and truck brakes, digital systems require many of the new oscilloscope capabilities for their design and repair.

Particularly acute is the need at the digital-to-analog interfaces. Here, where both voltage levels and timing are important, the oscilloscope proves invaluable.

Process-control electronics of necessity are field installations where use of portable oscilloscopes predominates. For larger computer installations, both portable and laboratory models are often used. A typical application in the computer field is examining the working of on-line storage units such as disks. Another is power-supply check-out.

For looking at multiple-channel information, however, new instruments are increasingly called upon to supplement the oscilloscope. Logic analyzers, which typically offer 8, 12, 16, or 32 parallel channels, special test plug-in controllers, and self-diagnostics are some of the up-and-coming alternatives.

At some point, IC technology may be capable of producing an oscilloscope on-a-chip, and at that time oscilloscope prices are certain to fall. Until then, however, indications are that more progress will be made in value (or cost–benefit ratio) than in price reduction. More functions, more rugged construction, better repairability, and easier calibration will be the main areas of improvement.

Low-frequency oscilloscopes have shown particular growth in value in recent times. Portables, too, have added much advanced capability with relatively small cost increases. Many digital add-on features will be included in less expensive analog oscilloscopes. The availability of economical microprocessors, supporting memory, and fast analog interface IC chips will be an important factor here.

The prospect for the future is that oscilloscopes will change even faster. Programmability, ability to record and play back instructions to the user, more help from instrument intelligence—all are in the wind. ◆

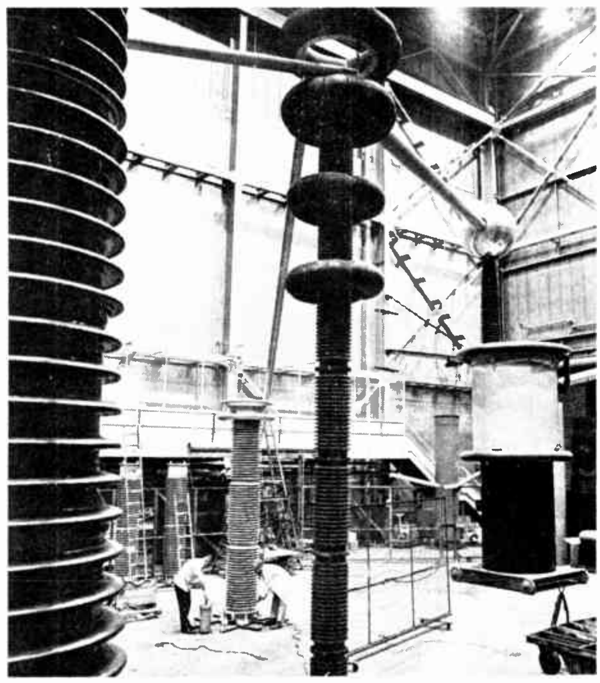
Leon Orchard (M) is general manager of the Service Instrument Division at Tektronix, Inc. He came to Tektronix from Clark College, Vancouver, Wash., in 1960, starting as a calibration engineer. In 1963, Mr. Orchard was promoted to staff engineering manager. He became electrical evaluation manager in 1964 and portable oscilloscope engineering manager in 1971. He was promoted to his present position in August 1975.

William Peek is general manager of the Laboratory Instrument Division of Tektronix, Inc. Starting as design engineer in accessories, he held a number of positions in instrument design groups, including that of engineering manager of the Spectrum Analyzer Department and manager of hybrid circuit design. From these positions he was promoted to his present position in August 1975. Mr. Peek received the B.E.E. and M.E.E. degrees from Oregon State University.

It's 75 for NBS

'Born' in 1901, the U.S. National Bureau of Standards promotes compatibility, reliability, and availability of electrical measurements

When an Act of the U.S. Congress established the National Bureau of Standards 75 years ago last month, it was answering a desperate need to bring order from chaos in U.S. industry and commerce. Measurement problems caused by a lack of national standards were proliferating throughout the country. Eight different "authoritative values" for the U.S. gallon were in existence. City surveyors in Brooklyn, N.Y., recognized as legal four different "feet."



A 500-kV, three-stage cascade, metering-accuracy potential transformer being calibrated in General Electric's high-voltage laboratory in Pittsfield, Mass. Calibration is carried out using the NBS high-voltage field calibration system consisting of a current comparator bridge and low- and intermediate-voltage compressed-gas standard capacitors, all of which can be transported to the site in a station wagon or small van. One of the capacitance standards, rated at 20 kV, is visible at the base of the test piece.

In the electrical industry, electrical developments advanced by wasteful trial-and-error methods for lack of definitions that neither scientific institutions nor industry were qualified to provide. And, in the emerging electrical instrumentation field, instruments invented and manufactured in the United States were sent routinely to Germany for calibration before they were sold in the U.S. or elsewhere. The situation was so intolerable that Carl Hering, then president of AIEE, felt compelled to send a telegram to the House of Representatives in which he not only urged passage of legislation to establish a national bureau of standards, but also described the standardsless conditions then extant as a "national humiliation."

In the ensuing 75 years, NBS has fulfilled its charter well. It has maintained custody of U.S. national standards; has compared standards used in scientific investigations, engineering, manufacturing, commerce, and educational institutions with the standards adopted or recognized by the U.S. Government; has constructed standards when necessary; has tested and calibrated standard measuring apparatus; and has determined physical constants and the properties of materials when such data were of importance to scientific or manufacturing interests and could not be obtained elsewhere with sufficient accuracy.

In today's technology-intensive world, NBS still plays essentially the same role, but the problems and their solutions tend to be different. For example, the emphasis has shifted from artifacts to nature's constants and from a need for transporting instruments requiring calibration to NBS facilities to high-precision transportable standards and to standards easily reproducible in the field. The new emphasis is part and parcel of what NBS—or, more specifically, the Electricity Division of NBS—refers to as its electrical measurements program; a program with the overall goal of ensuring the compatibility, reliability, and availability of electrical measurements in a cost-effective way throughout the U.S. (At NBS, the electromagnetic spectrum is "shared" by the Electricity Division located at the main NBS site in Gaithersburg, Md., which has responsibility for dc and low-frequency measurements; and the Electromagnetics Division located at the NBS Boulder, Colo., laboratory, which emphasizes RF and microwave measurements. This article covers only the work of the Electricity Division.)

The Electricity Division orients its electrical measurements program to the three prime segments of its user community. These three segments, as identified by NBS, are industrial electronics (which includes consumer electronics), electric power, and the scientific community.

Industrial electronics

Industrial electronics, in the NBS view, can be divided into a measurement-intensive area and a general industry area. (These conclusions and those following will be discussed in detail in a forthcoming publication of the Division entitled, "Electricity Divison Study of the National Electrical Measurement System.") Measurement-intensive industry and its measurement systems are characterized by high technology and the need for a high degree of product reliability. Typical examples are the instrumentation, aerospace, defense,

Ronald K. Jurgen Managing Editor

communications, computer, and electronic component industries. Measurement accuracy within this segment is ensured by a hierarchical laboratory system in each industrial organization. Test equipment used for quality and process control is calibrated periodically using precision instruments, which, in turn, are calibrated by comparison with primary standards in the corporate standards laboratory. These corporate primary standards are then calibrated periodically at NBS or intercompared regularly with standards that have been so calibrated. This system, which in large organizations can have a complex hierarchy of laboratories, is primarily the result of the quality control requirements of the U.S. Department of Defense (DoD), General Services Administration, and NASA procurement contracts, and the requirements of regulatory agencies such as EPA and OSHA.

In general industry, quality control requirements are usually less stringent than in the high-technology segment. Accuracies are generally lower and the manufacturing processes are less affected by absolute accuracy of measurements. General industry organizations are inclined to buy calibration and repair services from instrument manufacturers, large corporate laboratories in the aerospace industry, or companies specializing in calibration and repair work.

Measurements made in support of consumer electronics such as television, stereo systems, citizen band and amateur radio, automotive electronics, and general electrical work are usually of low accuracy. Consequently, manufacturers' claims of test equipment accuracy are accepted until malfunction occurs. There would appear to be few, if any, serious technical problems in this area.

In the nonconsumer electronics areas of industrial electronics, however, there are a number of problems and shortcomings, according to NBS. Among the most important are a lack of standards (both written and artifact) for the support of dynamic, high-speed electric measuring instruments and automated test systems; the nonavailability in certain areas of procedures and test techniques of guaranteed reliability; a potential future shortage of competent measurement personnel; a failure on the part of some people to perceive that calibration is not always a sufficient condition for assurance of measurement quality; and an inherent complexity in Government contractual requirements that can stifle innovative approaches to measurement problems.

Electric power industry

NBS sees the electric power industry as made up of an operational segment and a research segment for improved electric power transmission and distribution. In this industry, measurement support for both the operational and research segments is generally provided by the measurement laboratories of power companies and those of the electric equipment manufacturers. In the energy metering area, many of the state and local public utility commissions that regulate the power companies require acceptance testing of new watthour meters as well as retesting of older meters. NBS calibration of physical standards and electric apparatus, both at NBS and in the power companies' and manufacturers' laboratories, ensures overall system integrity.

Most of the industry—utilities and manufacturers alike—is well equipped to measure traditional quantities such as current, voltage, and power at levels up to 15 kV. Fewer companies, especially in the utility sector, have high-voltage capabilities above 100 kV. At existing EHV levels (to 765 kV) and at projected UHV levels (above 765 kV), the utility companies, with rare exceptions, have little measurement and calibration capability. However, such capability does exist with the manufacturers of large electric equipment. With respect to specialized measurements required in equipment testing and R&D, such as measurements of high transient voltages and currents, and insulation properties, measurement capability is generally available only with equipment manufacturers.

The energy crisis has already placed additional strains on the overburdened electric power transmission systems in the U.S. New techniques, such as concentrating power generation in mine-mouth plants and nuclear parks at a relatively few sites away from urban areas, will further aggravate the situation. Greatly expanded overhead transmission facilities will be needed to transmit the remotely generated power to the suburban fringes and new underground lines will be needed to bring the power into metropolitan areas. At the same time, it will be essential that energy losses, overall transmission costs, and effects on the environment be minimized. New high-voltage and electrically related measurements will be required as transmission technology advances. Cryogenic transmission systems, UHV overhead lines, compressed-gas insulated substations, and HVDC transmissions are all examples of relatively measurement-intensive emerging technologies.

Although older measurement methods and instruments can sometimes be adapted for these new areas, generally they will not lead to cost-effective, reliable and sufficiently accurate solutions. Thus, in parallel with the introduction of new T&D materials and systems, new measurements and test procedures must be developed to determine their reliability and life expectancy. Specialized precise measurements often have to be coupled with the understanding of basic mechanisms of failure. Examples of areas requiring further attention are measurements and tests to predict aging rates and life expectancies of insulation systems; and measurements of EHV and UHV transients, particularly those with steep wave fronts in the nanosecond range.

The scientific community

Measurements made in laboratories in the scientific community are generally supported by local instrumentation shops. In contrast with the usual practice in industrial electronics, periodic recalibration is unusual. Calibration is normally performed only before and after a crucial experiment, or as part of a special maintenance effort.

One of the most useful outputs of the electrical measurements program for the scientific community is the determination of the numerical values of certain fundamental physical constants and conversion factors that are closely related to the electrical units maintained by NBS, such as the Faraday constant. Determining such quantities to ever greater levels of accuracy can be of great importance because they often provide information concerning the overall correction of the basic theories of physics themselves. It is also a good way to advance measurement science since "adding the next decimal place" always requires advancing the state of the art.

Compatibility, reliability, availability

Compatibility, reliability, and availability are the three key words in the electrical measurements program. Compatibility means that electrical measurements made in one part of the country are consistent with those made in another. It can be achieved, for example, by having traceability to national standards of the fundamental units such as the volt and ohm; and it is a necessary requirement to ensure interchangeability of components and equity in trade between buyers and sellers. Closely related is the compatibility of U.S. electrical measurements with those of other countries. International compatibility is achieved by NBS participation in international comparisons of electrical standards and in the work of international standardizing committees.

Reliability means that electrical measurements made in the U.S. are accurate. Accuracy is achieved by traceability to national standards, by measurement assurance programs or MAPs (to be described later) to evaluate specific measurement processes, and by the dissemination of NBS publications that give preferred measurement procedures and related information. Reliability of electrical measurements ensures compatibility and the proper functioning of instruments and systems.

Availability means that the electrical measurement community has adequate methods to perform the electrical measurements required for the timely advance of science and technology. For example, NBS has a project underway to develop a high-accuracy technique for measuring low-level alternating voltages at sub-hertz frequenices in order to improve vibration and shock testing.

Implementing the program

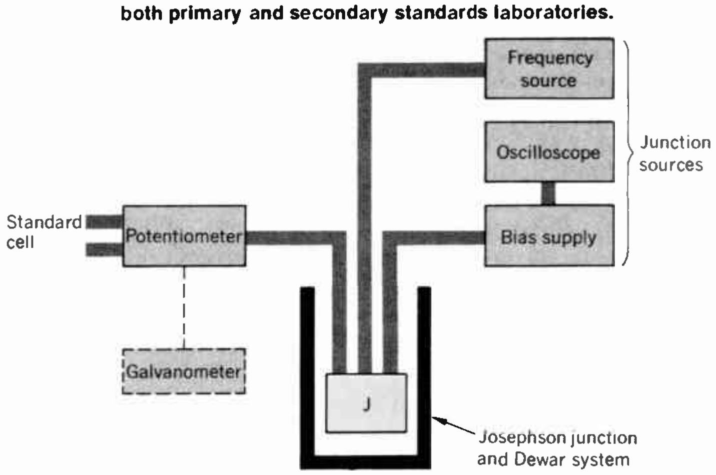
To achieve the overall goal of the electrical measurements program—which, simply stated, is to provide the central basis of a complete and consistent system of electrical measurement within the U.S.—NBS has specific projects designed to meet specific needs in each of the three prime segments cited earlier: industrial electronics, electric power, and the scientific community. Space limitations preclude describing all but a few representative projects, but key areas of each segment will be touched upon.

In the industrial electronics segment, the Electricity Division's current work may be conceptually divided into two parts: that dealing with fundamental measurements and standards of essentially a static nature, which are related to the basic electrical units such as the volt, ohm, and farad; and that dealing with dynamic or high-speed electric measuring instruments.

The work underway in the electric power segment may also be divided into two parts: that dealing with basic measurements of voltage, current, and power at high voltages; and that related to the development of improved electric power transmission and distribution systems.

As previously noted, the Division's most important work for the scientific community is the determination of certain fundamental physical constants.

Block diagram of a rugged, portable, and highly reliable Josephson-effect voltage standard that is presently under development at NBS. The Josephson junction acts as a voltage reference for the potentiometer, which is used to calibrate standard cells and other voltage references. It is expected that the instrument will be commercially available for use in both primary and secondary standards laboratories.



Measurement assurance programs

NBS has become increasingly aware that its measurement services must be oriented toward the solution of the measurement community's real-world problems. One important part of this philosophy is to help industrial users of instruments assure the integrity of their internal measurement systems on a day-to-day basis; to warn them when their measurement processes are going, or have gone, out of control; and to be certain that their measurements are made in a cost-effective way, e.g., not made more accurately than is necessary for the particular electrical measurement application.

To meet these objectives, NBS has launched what are called measurement assurance programs—programs tailored to specific industry measurement needs. MAPs are available in the areas of direct voltage, resistance, capacitance, electric energy (watthour meters), and direct-voltage ratio, and for various high-voltage quantities for which the equipment is too large to move, or of a rated voltage that exceeds the maximum voltage available at NBS.

One example of a MAP is the Volt Transfer Program, in which carefully chosen and well-tested transportable voltage standards (standard cells in thermoregulated enclosures) are sent to a client's laboratory under carefully controlled conditions. The client calibrates these cells (whose emfs are unknown to him) using the equipment, operators, and conditions he normally uses to calibrate his own workload. The only difference is that data are taken from a redundant measurement set (the result of a statistical design of intercomparisons of standards) whose design is supplied by NBS. These data are then analyzed by NBS for the purpose of evaluating the client's measurement capability and to see if his measurement process is under control. Problems that show up in the analysis at NBS are often solvable by a simple phone call to the client. The analysis process can determine such problems as the existence of unnaturally low leakage resistances, ground currents, temperature anomalies, and other insidious problems. A calibration of the client's standard also results.

Josephson-effect voltage standards

Maintenance of the U.S. legal volt is the responsibility of NBS and, since July 1972, the U.S. legal volt has been routinely maintained at NBS by measurement of $2e/h$ (where e is electron charge and h is Planck's constant) via the Josephson effect to an accuracy of a few parts in 10^8. Present R&D work is centered around two main objectives: to develop a reliable, easy-to-use, all-cryogenic voltage standard that is accurate to approximately 1 part in 10^8 to replace the room temperature system presently used to maintain the volt; and to develop a rugged, portable, and highly reliable voltage standard with an accuracy of 1 ppm for use in other standards laboratories.

The work underway will enable NBS to disseminate the legal volt more accurately to other Governmental, educational, and industrial organizations. Presently, the ac Josephson effect is the most precise way of maintaining a unit of voltage since the effect is related to invariant constants of nature. Development of a reliable, easy-to-use, all-cryogenic voltage standard will result in the reduction of operating costs for maintaining the legal volt as well as a significant increase in its precision. The availability of a portable voltage standard will reduce to a large degree the amount of effort now required by other laboratories to maintain a reliable voltage standard with only standard cells.

A/D conversion methods

The introduction of time as a critical parameter in electrical measurement has resulted from the requirements of automatic test and control systems. A key area is dynamic performance characterization for modern signal conditioning and data conversion devices such as D/A and A/D converters, sample-and-hold amplifiers, and comparators. To help identify the most critical needs in the high-speed electrical measurements area, NBS held a workshop in September 1974, bringing together a number of manufacturers and users. (The workshop report, NBS Technical Note 865, entitled "Critical Electrical Measurement Needs and Standards for Modern Electronic Instrumentation," SD Catalog No. C13.46:865, $1.35, is available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.)

In response to this need for time as a critical parameter in electrical measurement, NBS has initiated a program for evaluating and testing A/D and D/A converters and is becoming involved in work with the IEEE A/D and D/A Converters Subcommittee to establish paper standards of terminology, performance criteria, and recommended test methods. It is hoped that the R&D program not only will lead to a calibration service for converters but will also establish a proving ground for evaluating and recommending other proposed testing techniques that prove suitable for implementation by the users themselves.

For the initial program, two high-accuracy D/A converters are under development to be used in conjunction with analog comparators and a minicomputer. One is a low-speed device employing relay switching; the other is a medium-speed D/A converter using semiconductor switching. These converters will be utilized primarily for testing high-resolution, lower-speed converters. Some tradeoffs between speed and accuracy of the systems employing them is expected. Extension of the program to higher speeds is anticipated as expertise and experience at NBS develop.

High-voltage calibration *in situ*

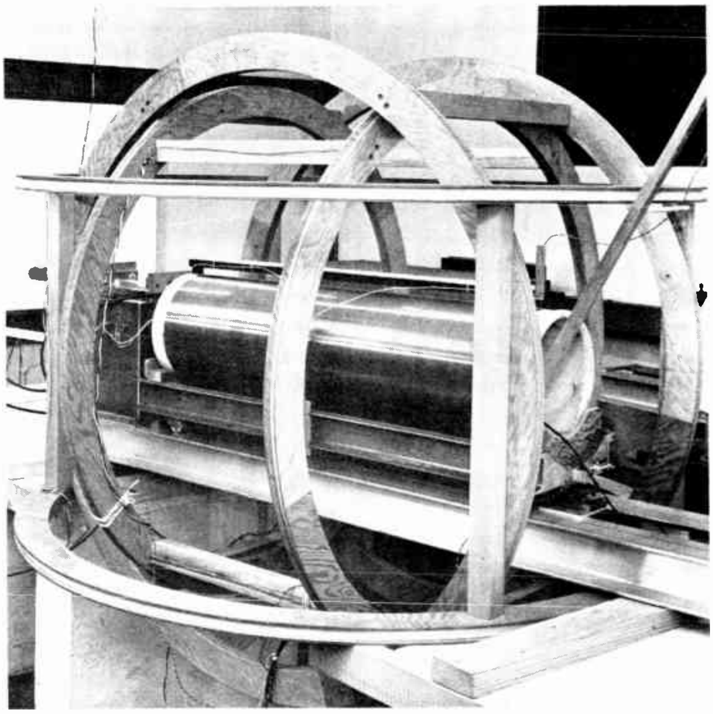
In the electric power field, NBS has a form of measurement assurance program for calibration of high-voltage equipment *in situ*. The very size of such equipment makes its movement impractical. The measurement assurance program not only permits the equipment to be calibrated in the environment and place where it will be used, as it will be used, but also gives NBS staffers an opportunity to transfer NBS measurement methodology to the client's laboratory personnel on a person-to-person basis.

NBS has constructed special current comparator bridge with an accuracy of 10 ppm. This bridge, together with low- and intermediate-voltage, compressed-gas dielectric capacitors, constitutes a system that is easily transported to a field site. The system can be used by a two-man crew to calibrate potential transformers, high-voltage capacitors, shunt reactors, and other high-voltage gear.

Kerr-effect voltage measurements

The need for measurement of pulsed high voltages (pulses with rise times of 1 ms to 1 ns and peak values from 1000 to several million volts) to an accuracy of 1

Apparatus used at NBS for low-field determination of the gyromagnetic ratio of the proton. The dimensions of a helical coil or solenoid are measured accurately using a laser interferometer, computer-controlled measurement system, and the magnetic field at the center of the solenoid is calculated in terms of the current passing through it. The corresponding precession frequency of the protons in a water sample at the center of the solenoid is then measured using fairly conventional nuclear magnetic resonance techniques. The solenoid shown is wound with 1000 turns of wire in a single layer. The plywood frame surrounding the solenoid contains large coils used to eliminate the effect of the earth's magnetic field.



percent of peak value has prompted NBS to conduct research in high-voltage transient measurements. A key part of this work is the development of a novel Kerr-effect electrooptic technique for transient voltage and electric field measurements, and for the transfer of these measurements to users' laboratories. (To perform a measurement using the electrooptic Kerr effect, it is necessary to have a substance containing molecules with an electrical anisotropy. When a voltage is applied, these molecules will tend to align with the resulting field. The voltage measurement is made by measuring the degree of alignment using a laser.)

Accurate measurement of high transient voltages is made difficult by diverging demands on the measurement system. Whereas high voltages require large apparatus and wide separation of components to provide electrical insulation, the fast rise times—about 1 microsecond or less—require small geometries. Consequently, the state-of-the-art accuracy is orders of magnitude poorer than that achieved in steady-state high-voltage measurements. But accurate measurements are necessary in a number of important applications, including the testing of X-ray machines, nuclear devices, and high-voltage transmission system components, and for research into new types of energy resources and delivery systems.

The electrooptic Kerr effect is being developed by NBS as a primary method for measuring high-voltage pulses. Present research is concentrated in three areas. The first is an investigation of the behavior of various liquids suitable for use in a pulse voltage/electric field measurement system. The response of the Kerr system using these liquids is determined as a function of the frequency of the applied voltage, wavelength of the light, and liquid temperature. The second area is concerned with accurate calibration of Kerr-effect voltage-measurement systems to determine their precision and stability. The final area of Kerr-effect research is the extension of this measurement system technique to both higher voltages (above 300 kV) and longer pulse lengths.

Insulators at cryogenic temperatures

Another NBS project in the electric power field is aimed at providing measurements of dielectric losses in insulators at liquid helium temperatures (~4 K). The immediate need for these measurements is to help decide on the best insulation for a prototype superconducting cable being developed by ERDA. The choice of insulation for this flexible, tape-wound cable is governed by a number of engineering constraints—both mechanical and electrical.

The basic engineering problem that the measurements address is that of dielectric heating. It is a consequence of the nonideality of insulation. That is, in a capacitor filled with a nonideal dielectric, the current will not lead the voltage by exactly $\pi/2$ but will instead be somewhat less than this angle. The closer the current–voltage phase relationship is to $\pi/2$, the smaller the heat dissipated in the dielectric. For superconducting cables now on the drawing board, a dielectric whose current–voltage phase relationship differs from $\pi/2$ by more than 2×10^{-5} radians will contribute a significant load to the cable refrigeration system.

The measurement of such small losses at high electric stress and at temperatures near absolute zero is a problem in metrology that few laboratories are capable of solving. NBS, however, has developed a high-voltage current comparator bridge capable of resolving dielectric losses with an accuracy of 1×10^{-6} radians. This precision not only allows the evaluation of the relative merits of different insulators but also makes it possible to study the effects of high fields on the dielectric.

Gyromagnetic ratio of the proton

To a nonphysicist, improved accuracy in the measurement of the gyromagnetic ratio of the proton, γ_p, has little significance. But to the scientific community, it is an important advance. The gyromagnetic ratio of the proton is the ratio of the precession frequency of the proton (the spin axis of a proton precesses around the direction of an applied magnetic field much like the wobbling of a top) to the strength of the applied field. Although this ratio plays an important role in magnetic field measurements, its real significance is that it can be used, in combination with other constants, including $2e/h$ determined via the Josephson effect, to determine one of the most basic fundamental constants of physics, the fine-structure constant, α.

The fine-structure constant is the coupling constant or expansion parameter of quantum electrodynamics (QED), the theory that describes the interaction between fundamental particles and electromagnetic fields. It is one of the most important and precise of modern theories. As the expansion parameter of the theory, α is essential for comparing the theoretical predictions of QED with experiment.

The main problem in determining the proton's gyromagnetic ratio is measuring with sufficient accuracy the dimensions of the precision solenoid used to establish the precession field so that the field may be reliably known. Using modern dimensional measuring techniques (e.g., a laser interferometer), NBS has succeeded in obtaining the value of γ_p to an accuracy of 4 parts in 10^7 (0.4 ppm), with 0.2 ppm expected when the experiment is finished by year's end. When completed, this determination will yield an α value accurate to about 0.1 ppm, and will provide physicists with a factor-of-ten sharper tool for testing QED to unprecedented levels of accuracy.

The next 75 years

These necessarily brief descriptions of just a few of the measurement projects underway in the Electricity Division of NBS are an indication that NBS is keenly aware of present-day measurement needs and is doing something about them. Although some may feel that these needs are not as dramatic as they were 75 years ago, they are, nevertheless, still very real, and often very urgent.

With an ongoing policy of seeking out critical measurement requirements and instituting programs to meet them, thereby making it easier for industry to keep its measurement processes under control, NBS is assuring itself of a vital role in the U.S. measurement system for the next 75 years and beyond. ◆

Consultants for this report at the Electricity Division of NBS were: B. N. Taylor, chief of the division, W. E. Anderson, N. E. Belecki, R. F. Dziuba, B. F. Field, R. E. Hebner, Jr., H. K. Schoenwetter, and T. M. Souders. For additional information regarding the work of the Electricity Division, contact B. N. Taylor, Electricity Division, NBS, Washington, D.C. 20234.