A Portable, Low-Cost, High-Performance Digital Multimeter for the HP-IL

HP's first HP-IL instrument is the result of new design and manufacturing approaches. This DMM electronically calibrates itself, measures ac and dc voltages and currents, makes four-wire and two-wire resistance measurements, and uses a liquid-crystal display to output data, measurement units, and alphanumeric messages.

by Jack P. Trautman and Lawrence A. DesJardin

PORTABLE, ACCURATE MEASUREMENTS of voltages, currents, and resistances are a necessity for electronic service personnel and other users operating in the field. Large amounts of data often must be collected and analyzed. If this data can be output by the measuring device directly to a portable computer, the need for considerable manual effort to record the data and later enter it for analysis can be avoided. Low instrumentation cost is important because, unlike a laboratory situation where many persons can have convenient access to one piece of equipment, field personnel each require a dedicated set of equipment. High reliability can also reduce field support costs.

To satisfy these needs, HP developed a low-cost serial interface, the Hewlett-Packard Interface Loop (HP-IL).[1] This interface allows bench measurements by a high-performance digital multimeter to be coupled to the advanced computational power of a handheld computer. The 3468A Multimeter (Fig. 1) is the first HP instrument designed for use on the HP-IL. It is a low-cost, autoranging, 5½-to-3½-digit, five-function DMM with 1-μV sensitivity designed for bench and portable applications. A rack-mount version with identical features, the 3468B, is also available. This microprocessor-based instrument can measure dc volts, true-rms ac volts, two-and four-wire ohms, and ac and dc current. Its simple, fast, electronic calibration eliminates manual adjustments to provide a lower cost of ownership. The standard HP-IL interface on the 3468A allows complete programmability with small computers such as the HP-41 Handheld Computers or the more powerful HP Series 80 Personal Computers.

Features

Several important features are contained in the 3468A's small package. These include:

- **HP-IL for low-cost automation.** When the 3468A is con-

Fig. 1. *The HP Model 3468A Multimeter is HP's first HP-IL instrument. It has an alphanumeric liquid-crystal display, measures ac and dc voltage and current, and determines resistance by both two-wire and four-wire methods.*

nected to a handheld computer through the HP-IL, software can easily be developed that stores and analyzes data for many applications. For example, to measure temperature, an HP-41 can be used to linearize the output of a transducer device measured by the 3468A. Then, the HP-41 can be programmed to output the results in degrees Celsius or degrees Fahrenheit on the display of the 3468A. For audio and telecommunication applications, the 3468A can display power in dBm referenced to any impedance by using a simple HP-41 program. For applications such as testing resistor tolerance or performance of a device, the HP-41 can easily get data from the 3468A, perform a percent-error calculation, and display the results in percent on the 3468A. The software and documentation for the 3468A include bar-code programs for the HP-41 that reduce system programming time. Peripheral devices, such as the 82162A Thermal Printer and 82161A Cassette Drive, are available to expand an HP-IL system to provide data recording and mass storage.

- **Interrupt capability.** The front-panel **SRQ** key on the 3468A allows the user to interrupt a running program on the computer controlling the 3468A and cause it to execute another program.
- **High-performance bench measurements.** The 3468A can measure dc and true-rms ac voltage in several ranges from 0.3V to 300V full scale, with 1-μV to 1-mV sensitivity, respectively. This wide dynamic range enhances the number of measurements that can be made with the 3468A. The 3468A's ac converter is true-rms-responding, and provides accurate detection of nonsinusoidal waveforms with crest factors up to 4:1. With a bandwidth of 100 kHz on all ranges and an extended bandwidth of 300 kHz on the 30V range, the 3468A provides a broad range of ac detection. Resistance measurement ranges from 300 ohms to 30 megohms with respective sensitivities of 1 milliohm to 100 ohms are available for both two-wire and four-wire measurements. The four-wire ohms function can be used to reduce errors caused by lead resistance and the two-wire ohms function is convenient for bench measurements. Both dc and true-rms ac current measurements are provided up to 3A. All functions on the 3468A incorporate fast autoranging to provide answers quickly and accurately.
- **Smart display.** The 3468A DMM uses an easy-to-read, 14-character, alphanumeric liquid-crystal display that provides measurement units as part of the reading for unambiguous answers. Annunciators below the reading show instrument status and the status of the HP-IL interface. With the HP-IL interface, words or messages can be arbitrarily displayed on the 3468A for prompting or displaying answers in calculated units such as degrees or revolutions per minute.
- **Rechargeable battery.** The optional battery pack includes a rechargeable battery and charging circuitry to allow up to five hours of continuous portable measurements. For applications in the field, the 3468A and other battery-powered HP-IL devices can be set up to provide a completely portable measurement system.
- **Electronic calibration.** Complete calibration of the 3468A is done electronically without any internal manual adjustments. All functions can be calibrated either from the front panel or remotely by an automatic calibration system.

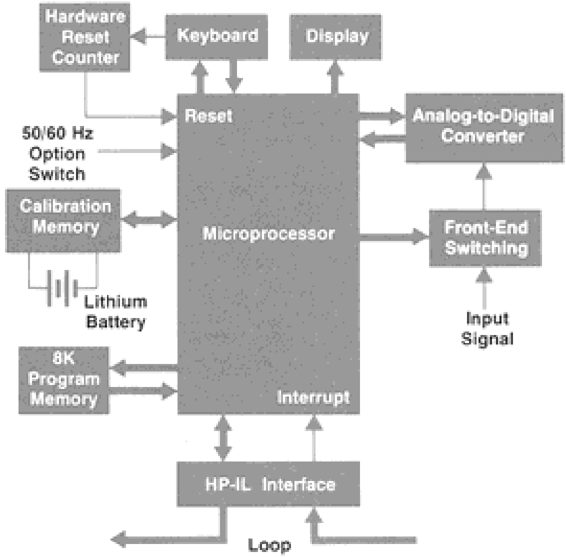

Fig. 2. *Simplified block diagram of 3468A.*

- **Self-test.** The 3468A has a built-in self-test feature initiated by pressing the **TEST/RESET** key on the front panel. A comprehensive check of both analog and digital circuits is performed while activating all display segments. Upon successful completion of self-test, the message SELF TEST OK is displayed.

A Look at the Design

The 3468A achieved its goals of low cost, reliability, and high performance by a conscious effort to select each component of the voltmeter not only in terms of performance, but also in terms of producibility.[2]

A look at Fig. 2 reveals that the 3468A's block diagram is similar to the block diagram of a conventional voltmeter. The input signal is transformed by the signal conditioning circuitry of the front end to a voltage between +10V and −10V (±3V in the ac modes). This voltage is digitized by the analog-to-digital (A-to-D) converter to the resolution selected by the user. The microprocessor controller linearly corrects this value using constants that have been stored in the nonvolatile calibration memory for this particular function and range. The corrected value is shown on the liquid-crystal display of the front panel and can be output onto the HP-IL.

The photograph of the interior of the 3468A (Fig. 3) shows that the design of the instrument is much less conventional. A single printed circuit board houses all the electronics but the display. Several contrasts with conventional voltmeters can easily be noted. The first is the absence of Teflon™ standoffs, previously considered a necessity to ensure high impedances on precision analog boards. A special process was developed that guarantees high impedances across the board's surface as long as the surface remains clean. A vigorous program of instituting clean handling was adopted to safeguard the integrity of the

HP-IB Version of 3468A

The 3478A Multimeter (Fig. 1) is a low-cost HP-IB (IEEE 488) programmable instrument for system measurements. A companion product to the 3468A with similar display and measurement features, the microprocessor-based 3478A is an autoranging, 5½-to-3½-digit, five-function digital multimeter designed for automated testing in production or research and development. Its simple, fast electronic calibration eliminates all manual adjustments to provide a lower cost of ownership.

High Performance at Low Cost

The 3478A can measure dc voltage with 100-nV sensitivity on the 30-mV range up to a maximum reading of 300V. It can measure ac voltage from 300-mV full-scale range with 1-μV resolution up to 300Vrms. This wide dynamic range minimizes the amount of signal conditioning required to detect low-level signals and higher voltages. Either two-wire or four-wire resistance measurements can be selected with a maximum range of 30 megohms and a 100-$\mu\Omega$ sensitivity on the 30-ohm range. Both 300-mA and 3A ranges of ac and dc current are provided, completing the function capability of the 3478A. Fast autoranging improves system throughput by minimizing the time to select the correct range.

The 3478A can perform production tests or acquire experimental data at 71 readings/second with 3½-digit resolution, or obtain 33 readings/second with 130 dB of noise rejection using 4½-digit resolution. Increasing the resolution of the 3478A to 5½ digits reduces the measurement speed to 4.4 readings/second.

Designed for HP-IB Systems

All of the performance of the 3478A can be controlled over the HP-IB by a wide range of compatible computers. Complete programmability of functions, ranges, and other modifiers on the 3478A makes it ideal for use in a fully automatic test system.

With an extensive set of service request (SRQ) interrupt capabilities, including data ready, front-panel **SRQ** key, and power-on SRQ, the 3478A allows more flexibility in a system. The data-ready service request of the 3478A can be programmed to interrupt the computer after a measurement has been taken, allowing more efficient use of computer time. The front-panel **SRQ** key lets a system operator interrupt the computer from the 3478A's front panel. The 3478A can also flag the computer at power-on to indicate loss of power.

Switchable front and rear terminals on the 3478A permit convenient measurements at a bench using the front terminals or system inputs using the rear terminals. The setting of the front/rear terminal switch on the 3478A's front panel can be sensed remotely over the HP-IB, so both sets of terminals can be effectively used in any system configuration.

A **VOLTMETER COMPLETE** output on the rear panel of the 3478A provides a signal after a measurement is completed. This output can be used to advance a scanner to the next channel without computer intervention, thus enhancing scanning speed. An **EXTERNAL TRIGGER** input is also provided on the 3478A to initiate measurements and synchronize with an external device.

Fast Electronic Calibration

Like the 3468A, complete calibration of the 3478A is done electronically without any internal manual adjustments. All functions can be calibrated either from the front panel or remotely in an automatic calibration system.

Fig. 1. *The HP Model 3478A Multimeter is the HP-IB version of HP's new, low-cost, high-performance digital multimeter design. It combines the display, measurement, and electronic calibration features of its companion instrument, the 3468A, with HP-IB operation capabilities and higher performance.*

boards. Elimination of the standoffs significantly reduces the amount of manual labor required to assemble the voltmeter, and thus lowers its cost.

Electronic Calibration

Even more conspicuous is the absence of any manual adjustments or "tweaks." This is achieved by a design that forces significant imperfections (e.g., voltage offsets, imperfect resistor matching) to be linear errors, that is, errors of offset and gain. This allows readings to be corrected by simple math routines that subtract the offset value and then perform a multiplication to scale the final answer correctly as follows:

$$R = (R' - Y)G$$

where R is the final calibrated reading, R′ is the raw uncalibrated reading, Y is the offset correction factor, and G is the gain correction factor.

The correction factors Y and G are unique for each dc and ohms range, and are stored in a CMOS memory that is kept continuously powered by a lithium battery (seen in Fig. 3). Even when the rest of the instrument is not powered, the memory contents can be kept valid for over ten years by the lithium battery. The values of Y and G are derived by the 3468A's microprocessor and loaded into the memory by an electronic calibration procedure. This allows the user to calibrate the instrument without removing the covers or turning a single screw.

Initially, the user sets the instrument to the function and range to be calibrated. The offset must be calibrated first, so a short is placed across the input terminals and the user

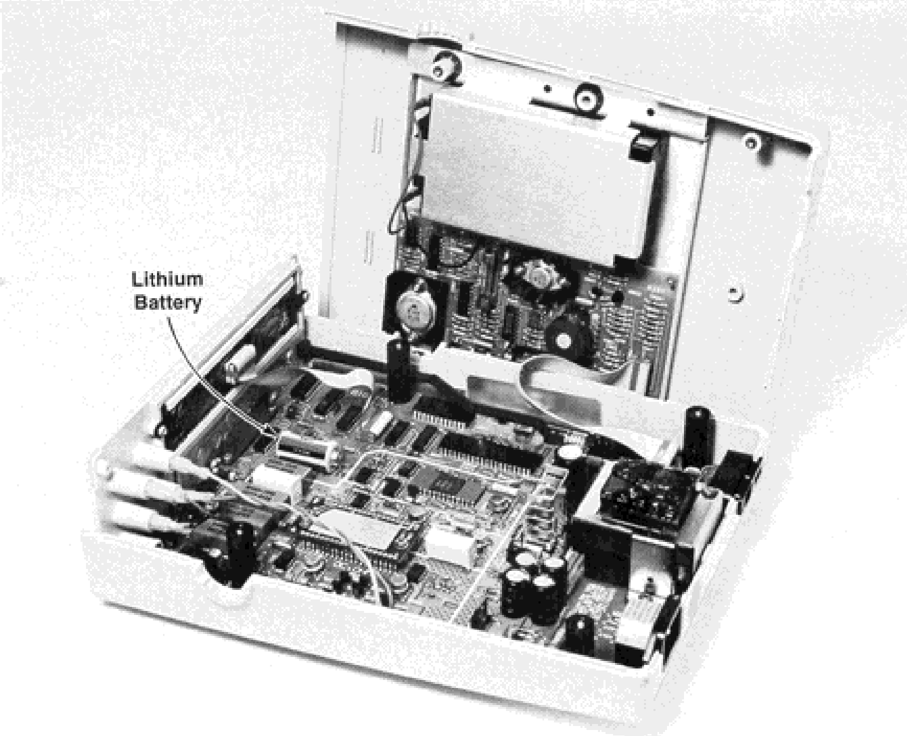

Fig. 3. *Interior of 3468A. The electronics system, with the exception of the liquid-crystal display, is mounted on a single printed circuit board. No Teflon™ standoffs or potentiometers are used.*

enables the **CAL** function. The 3468A takes a single measurement, recognizes that the reading is close to zero, assumes that the user wishes to calibrate the offset, and displays 0.00000? The user now presses the **SGL TRIG** key to verify that zero was indeed the user's target value. The 3468A averages ten 5½-digit readings to derive the new Y value, and stores this constant in the calibration memory. The display then reads CAL DONE, and returns to normal operation.

Using an external standard, the user can now apply the full-scale value of that particular function and range to the meter and repeat the previous procedure. Again, ten 5½-digit readings are taken and averaged. However, this time a divide operation is performed to determine the value of G, and the new value is stored into the calibration memory.

It is possible that a user may own a standard that is very stable and known in value, but not exactly equal to the 3468A's full-scale value. Furthermore, many standards are in cardinal values of 1 or 10 instead of 3, the 3468A's full scale. To accommodate both of these common situations, the 3468A quickly measures the applied signal and displays a target value of 100000? or 300000?, whichever is closest to the measured value. Using the front-panel's ⇑ and ⇓ keys, the user can then increment or decrement the display to the exact value of the standard used. Pressing the **SGL TRIG** key then commands the instrument to calibrate to the altered target value.

Calibration of the ac modes is done in a slightly different manner. On ac ranges, the nonlinearity of the true-rms converter allows it to operate accurately only from one-tenth to full scale. A shorted input would give an inaccurate Y value, as can be seen in Fig. 4. In many conventional voltmeters, the ac calibration procedure requires that the applied signal be varied between one-tenth scale and full scale while a technician adjusts two interactive controls. To calibrate all the ac modes on the 3468A, a single 3Vac signal is applied. The target value can be adjusted to the exact value of the signal, using the ⇑ and ⇓ keys, and then pressing the **SGL TRIG** key will calibrate all ac functions.

Internally, the 3468A switches the ranges so that it has one full-scale reading and one tenth-scale reading, much like the technician calibrating a conventional voltmeter. However, instead of having to converge on the correct constants iteratively, the 3468A solves two simultaneous equations exactly for Y and G. This can be done because most of the uncalibrated inaccuracies are common to all ac voltage and current ranges. The uncalibrated reading taken on the 3Vac range will be close to full scale and is labeled FS. The uncalibrated reading taken on the 30Vac range will be close to one-tenth scale and is labeled TS. T is the target value. With the correct choice of Y and G, the following equations must be true:

$$T = (FS-Y)G$$

$$T/10 = (TS-Y)G$$

The 3468A solves for G first. Thus,

$$G = 0.9T/(FS-TS)$$

and Y is then solved for by:

$$Y = FS - T/G$$

When these constants are loaded into the calibration memory, the display reads CAL DONE and returns to normal operation. All of the calibration procedures can also be performed over the interface loop.

Much design effort was expended to insure the integrity of the calibration memory once the instrument is calibrated. To prevent unintentional writes into the memory, a switch located on the rear panel must be placed into the enable

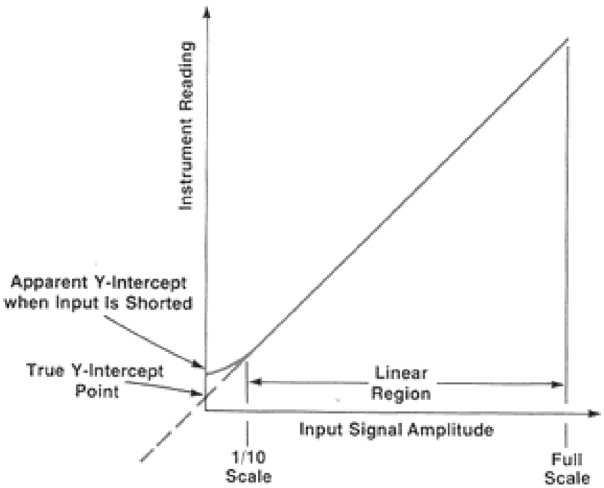

Fig. 4. *On ac ranges, the response of the true-rms converter is not linear below one-tenth full scale as shown above. The electronic calibration technique used in the 3468A takes two values corresponding to the one-tenth full-scale and full-scale readings and then solves two simultaneous equations (see text) to derive the true Y-intercept and gain (slope).*

position to allow the processor to write to the memory. This hardware failsafe prevents the user from unintentionally calibrating the instrument or altering the memory via the interface loop.

Although the 3468A is designed to withstand large electrostatic discharges (ESD), secondary safeguards are instituted for the calibration memory. Because the 256×4-bit memory selects a row of data at a time, it is possible that an entire row of data could be altered during ESD. For this reason, the data is addressed so that the calibration constants of any particular function and range are all located within the same row. If this row of data is altered, only that function and range will be uncalibrated, thus avoiding the need for recalibrating the entire instrument. Whenever the instrument is placed in that function and range, the CAL annunciator on the display is enabled, warning the user that the reading is no longer valid. Simultaneously, the appropriate bits are set in the 3468A's status bytes to notify the interface loop controller.

Besides ESD, there is also a small chance that an alpha particle or a cosmic ray may alter a single bit of the memory. To protect against this rare occurrence, the two constants for each function and range have parity bits associated with them so that the 3468A's microprocessor can locate single-bit errors and detect double-bit errors. The processor can correct a single-bit error in a calibration constant and the instrument will remain calibrated. If the processor detects more than a single-bit error, the CAL annunciator is displayed and the error bits are set to warn the user that the readings are uncalibrated. When this type of error is detected, the processor uses default values of zero for Y and one for G.

Electronic calibration not only simplifies calibration for the user but, by eliminating manual adjustments, the long-term stability and reliability of the product are improved. Furthermore, since the calibration routines can compensate for gain errors as high as 4.5%, many components can be chosen for their good stability and initial accuracy becomes noncritical. Potentiometers are not the only parts to be eliminated; there are neither jumpers to be inserted or removed nor components with individually selected values in the 3468A.

Microprocessor Design

It is principally by extensive use of the 3468A's microprocessor that such high performance is realized at low cost. Since the entire instrument is isolated from the HP-IL at the loop interface, there is no electrical reason why the system processor must be separate from the signal processor, as required in a guarded HP-IB (IEEE 488) instrument. In the 3468A, these tasks are combined and executed by a single 8-bit microprocessor.

Fig. 2 also shows how the processor interfaces with other sections of the multimeter. Besides executing instructions as they appear over the interface loop, monitoring the keyboard, and operating the display (typical system operations in a conventional system voltmeter), the processor implements a multislope analog-to-digital (A-to-D) algorithm,[3] and configures the front-end switches for proper signal conditioning (typical signal functions). The processor also performs all the electronic calibration procedures and monitors the 50/60-Hz switch so that it chooses the A-to-D algorithm having the proper power-line-frequency rejection.

A hardware failsafe counter is added to reset the processor if it hangs up (possibly done by erroneously executing code in a lookup table). If the keyboard is not scanned at least every 2.5 seconds, this counter resets the processor to its initial state.

Since many functions of the 3468A need dedicated control for finite periods of time, many tasks of the processor appear to be in conflict with each other. The most difficult conflict to resolve is that of executing the A-to-D algorithm (a dedicated operation) while still monitoring the keyboard and interface loop for new commands, and executing them. Since a high-precision A-to-D conversion can take up to 400 milliseconds, a key press can be missed entirely if it occurs during a conversion. Also, to have to wait 400 ms before a loop command can be processed is unacceptable.

This conflict is resolved by adding a constraint so that any key presses or loop activity abort the analog-to-digital conversion, and the command is executed before another conversion begins. To guarantee that both the loop and the keyboard are monitored during a conversion, the HP-IL IC chip is allowed to interrupt the processor when loop data is available, and the A-to-D algorithm firmware was modified so that the keyboard is scanned between integration periods. Thus, the maximum time between scans does not exceed 20 milliseconds, which is less than the minimum duration of a manual key press.

To increase the usefulness of the 3468A in an HP-IL system, two other features are included in its design. A front-panel **SRQ** key allows the user to initiate a service request to the loop controller from the front panel and have the ability to write alphanumeric characters to the 3468A's display remotely from the loop controller.

The Philosophy Behind The Design

Early in the definition phase of the 3468A Digital Multimeter, very aggressive goals for low cost, reliability, and quality were set without sacrificing any of the measurement performance objectives. This was done to satisfy the cost pressures of the marketplace, and because high quality and reliability are performance measures that users are demanding. At this same time, HP's Loveland, Colorado facility was taking a close look at its design and manufacturing philosophies, trying to better understand how to design more quality and easier producibility into its new products and manufacturing processes.

The 3468A was chosen as a vehicle to change design and manufacturing strategies and demonstrate that quality is truly the key to achieving low manufacturing cost and high productivity simultaneously without sacrificing the product's measurement performance. The goal of this project was not only to develop a product that made a significant technical contribution, but to apply what was learned to improve future product design and manufacturing.

Definition Phase

Crucial to meeting these goals and increasing the performance/price ratio is a proper instrument definition. In a conventional definition phase, technologies and design alternatives are investigated with the primary goal of meeting the measurement objectives. At this time, there is usually less emphasis placed on quality and manufacturability issues. However, in the case of the 3468A, after a technique was demonstrated to meet the measurement objectives, it was also carefully scrutinized for manufacturability. If it did not meet all of the project objectives, it was rejected. This ensured that the 3468A definition was not only well suited for the marketplace, but also an ideal vehicle for improving product development and production philosophies.

Out of this definition phase came several dominant objectives that are the essence of the 3468A's design. The first objective was to minimize the number of components used in the product. It was felt that minimizing the component count would help maximize reliability, since overall product reliability is the sum of the reliability of the individual components.

A goal of designing the 3468A with less than 100 parts was set in the early investigation phase. To design a 5½-digit DMM with 100 parts was an aggressive goal and required a totally new design approach. The final 3468A has about 160 components, still a remarkable achievement!

Another objective that originated in the definition phase was to increase the use of automatic production steps and hence reduce the manual labor content in the product. However, minimizing the amount of labor is not universally the right thing to do. For example, machine-insertable components are sometimes more expensive than their manually inserted equivalents. In such cases, a careful analysis was done to select the most cost-effective component, taking into account the cost of labor, loading errors, and product reliability.

With the goals of minimizing part count and labor in mind, a closer look at the internal definition will reveal how these goals were met while simultaneously providing performance and reliability benefits to the user.

While a conventional multimeter design incorporates at least two microprocessors, by using clever algorithm partitioning and an interrupt-driven structure, it was found that a single microprocessor design would meet the 3468A performance requirements. A reduction in parts count, complexity, power consumption, and cost, and an increase in reliability are direct results.

The 3468A makes extensive use of custom hybrid circuits. Both the analog-to-digital hybrid and the input hybrid incorporate high-voltage CMOS ICs and precision integrated resistor networks to do signal switching and conditioning, logic decoding and measurement timing. The ICs reduce circuit complexity (parts count) and increase the multimeter's performance by using the matching and temperature tracking properties inherent in adjacent devices on the ICs.

One of the biggest decisions made in the definition phase was to design the 3468A without any manual adjustments. Instead, calibration is done electronically. Not only does this feature greatly reduce the parts count and assembly costs by eliminating hand-loaded potentiometers and associated circuitry, it enhances reliability and reduces drift caused by mechanical and thermal shock. Production-line labor is reduced by designing the instrument to be calibrated automatically under computer control via the HP-IL. And equally important, the user benefits by having front-panel calibration available.

A liquid crystal display (LCD) was chosen for the 3468A, primarily for its pleasant appearance, readability and alphanumeric capability. However, it also meets the product definition criteria by reducing the number of parts and assembly labor. An equivalent display using light-emitting diodes (LEDs) would need 31 more components than the LCD, all of which would require manual insertion into a printed circuit board. Furthermore, the LED display would consume more power (about 1.5W) than the LCD.

A one-piece, silicone-rubber keyboard was selected over a conventional keyboard array of individual, manually loaded keys. Not only does this silicone-rubber keyboard eliminate 23 parts, it provides an easy-to-actuate switch that also forms a gasket seal with the front panel, keeping dust and moisture out of the internal circuitry.

One final technology developed to meet the definition phase objectives is a custom printed circuit board process designed to maintain high impedances under all specified environmental conditions. This process eliminates the need for labor-intensive Teflon™ standoffs and allows direct automatic insertion of components in the printed circuit board.

Design Phase

In addition to striving to meet the objectives set in the definition phase, the laboratory project engineers added another goal in the design phase of creating a "perfect" design. What was meant by "perfect" was a design that not only met all its instrument specifications, but also was designed with components that were completely characterized, specified, and guaranteed to operate properly under the worst-case tolerance conditions.

To achieve this "perfect" design goal, the team placed significant emphasis on extensive testing of the early prototypes. Complete environmental, safety, abuse, margin, and accelerated life tests were run with the intention of wringing out all design problems as early as possible. When the prototypes were not being evaluated by engineers, they were placed in an oven at 65°C and operated in all possible modes in an attempt to induce failure. Periodically, the instruments were removed from the ovens and vibrated on a shake table to try to uncover sensitivities to mechanical shock and vibration. All failures and anomalies were carefully documented, and with the help of the quality assurance department and its component analysis group, an attempt was made to autopsy all failed components and throughly understand every problem uncovered.

A large amount of data was collected on instruments that were run through the environmental tests. These units were subjected to temperatures ranging from −40°C to +75°C and relative humidities up to 95% at 40°C. The data collected at these various conditions was statistically analyzed and compared against the theoretical specifications to ensure that all interactions of the design were thoroughly understood.

An innovative feature of the 3468A design phase, which proved crucial to meeting the quality goals, was the full-time assignment of a materials engineer to the project. This individual's job was to understand the design requirements of every purchased component thoroughly and use that knowledge to select the best vendor. The materials engineer discussed the expectation of "perfect" components with each vendor and then worked with the vendor to establish methods for achieving this goal. Overall, the response on the part of the vendors has been quite favorable, and work continues to further improve vendor relationships.

A final departure from the conventional design sequence was the early involvement on the part of manufacturing engineering. The team of manufacturing engineers established their own department objectives to meet the overall product goals. These objectives were to ensure that 100% good parts were delivered on time to the production line, and that the product went through an error-free manufacturing process. Given that a production cycle begins with 100% good parts, and no defects are introduced through the manufacturing process, it can be expected that all of the instruments will turn on and function properly without any intermediate testing. This is the goal of the 3468A manufacturing team, which represents a significant departure from conventional manufacturing philosophy.

To achieve their goals, the manufacturing engineers played an active role in working with the design engineers to maximize the producibility of the design. The design engineers consulted with the manufacturing engineers at each prototype phase to get suggestions on how to improve the producibility of the 3468A. Under the scrutiny of the manufacturing engineers, production-line workers assembled the prototypes and commented on assembly-related problems. These comments were compiled and a manufacturability review was held. The appropriate changes were incorporated in the next prototypes.

The goal of a "perfect" production process requires the complete characterization of major process steps. Machinery such as the automatic insertion equipment and the wave-soldering machine were statistically characterized and are monitored through the use of control charts. Conductive work surfaces and ground straps were added to work stations. Air ionizers, grounded soldering irons, and antistatic packaging are installed throughout the manufacturing area. New handling procedures help ensure that assemblies are not inadvertently contaminated during fabrication. Adequate documentation and training are a necessary part of these changes.

The entire production process is designed with manufacturability in mind. All intermediate tests and repair loops are eliminated. Instead, a single, fully automatic test and calibration system turns on, calibrates, and characterizes each instrument only after it is completely assembled. The HP-IL interface and electronic calibration of the 3468A made the design of this automatic system possible. Another feature is the automatic collection of data on each instrument. This data is analyzed on a run-by-run basis to look for trends or shifts in specifications. Thus the final test system also acts as a process monitor to detect problems as they arise in the production process.

Production Phase

With the transfer of the 3468A to production, the results of these efforts can finally be seen. With defect rate, turn-on rate, and failure rate goals firmly established, the actual results were compared against predictions. The first production run yield was 70%, a little short of the initial goal of 75%. However, yields have been steadily increasing and presently exceed 80%. The long-term goal of achieving a 96% turn-on yield appears to be achievable. Each defect that is found is fully documented and presented to a task force whose job it is to identify the source of the defect and correct the problem.

The 3468A experiment seems to be a success. It is being demonstrated that by changing design philosophies, the quality and manufacturability of products can be significantly improved.

Analog Design

The 3468A's precision analog sections are dominated by two custom hybrid circuits: a front-end signal conditioning hybrid and an A-to-D converter hybrid. Both consist of custom CMOS digital logic, low-leakage MOS switches, and precision thin-film resistor networks.

The microprocessor serially loads the front-end hybrid by using three port lines: clock, data and load. This data is transferred to a latch, which drives the MOS switches. The state of these switches, which include relay drivers, completely defines the signal conditioning and varies with the particular function and range of the voltmeter. The precision front-end hybrid requires one silicon chip and two resistor networks and is mounted on a custom high-impedance printed circuit board. Outside the hybrid circuit are the operational amplifiers that are the active components for the dc, ac, and ohms current sections. Four low-thermal-emf relays are switched by the hybrid when high voltages are a possibility. An integrated rms converter supplies a dc signal representing the ac signal value to the A-to-D converter.

The A-to-D hybrid consists of one CMOS chip and one resistor network mounted onto a standard 28-pin ceramic dual in-line package. The 3468A uses a modified Multi-Slope-II algorithm[3] for its A-to-D conversion. Five microprocessor lines into the hybrid determine the current to be summed by the integrator. A comparator on the chip measures the polarity of the integrator and sets a microprocessor input to the proper sign value. The integrator operational amplifier and two reference operational amplifiers are located off the chip.

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The authors wish to thank our fellow project team members. Their technical abilities and tenacity made the 3468A and 3478A products successes, and equally important, their teamwork and lively spirits made it a fun project to work on. George Hnatiuk designed the ohms current source, and did the layout of the input fineline resistor circuits. Kelly Wright designed the dc signal conditioning and the custom CMOS input IC. Ron Swerlein was responsible for the ac signal conditioning and rms converter design, while Gerry Raak designed the power supply, battery option, and liquid-crystal display. Much of the 3468A's electrical robustness and A-to-D converter linearity are results of the efforts of Wayne Goeke. Wayne also did the electrical de-

sign of the 3468B. Bill Miner was responsible for the 3468A mechanical design, and Doug Olsen did the 3468B mechanical design. The I/O software and hardware design was provided by Gary Stadele, whose technical maturity and guidance got us through the difficult times. Industrial design for the 3468A was done by Jon Pennington.

The project manager and pundit for the 3478A, the HP-IB version of the 3468A, was Ron Tuttle. Rich Wilson and Virgil Leenerts did the 3478A electrical design, while Ed Pennington did the mechanical design. Industrial design for the 3478A was done by Ted Crawford.

Norm Dillman designed the environmental test system and wrote the test software for both products. Si Sanders was the materials engineer for both products.

Joe Marriott was the section manager for the completion of the project.

A special word of thanks goes to our original section manager, Roy Barker. His managment style and support provided us the work environment necessary to try something different, and then prove we could make it work.

Finally, all of the functional areas within the Loveland facility deserve recognition. The 3468A and 3478A were division-wide projects that required the unwavering efforts of many individuals outside of the lab to be successful. To all of you, we give our thanks.

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Low-Cost and Portability Come to Data Acquisition/Control Products

Inexpensive, portable data logging with the flexibility of a data acquisition/control system is now within the budget of nearly everyone making transducer measurements.

by James J. Ressmeyer

THE 3421A Data Acquisition/Control Unit (Fig. 1), HP's newest low-cost data acquisition and control scanner, represents the first instrument of this type using the Hewlett-Packard Interface Loop (HP-IL).[1] Battery power and the unit's light weight allow a complete measurement system to be configured by adding an HP-41 Handheld Computer, an 82161A Digital Cassette Drive and an 82162A Thermal Printer/Plotter. This system (shown on the cover) can be easily transported and operated in the laboratory or field. Its low cost allows individual engineers

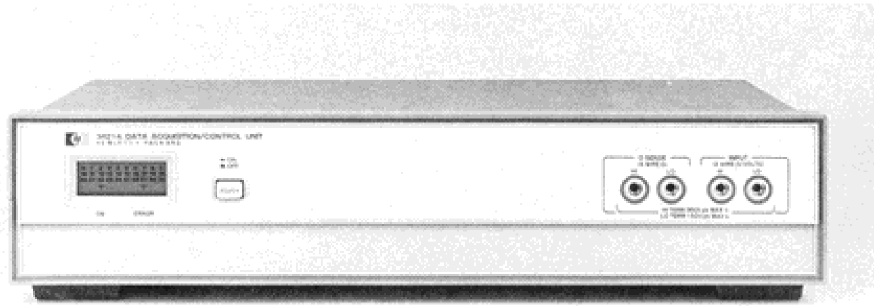

Fig. 1. *The HP Model 3421A Data Acquisition/Control Unit is a low-cost, battery-powered, up-to-thirty-channel instrument with an internal multimeter and counter designed for use on the HP-IL.*

to dedicate a system to specific measurements during the design or test phase of product development, and opens new possibilities for data acquisition applications.

The 3421A can be configured with up to 30 channels for measuring dc volts, ac volts, resistance or frequency through the use of three 10-channel multiplexing assemblies. These assemblies are directly connected to a 5½-digit multimeter contained inside the 3421A. The basic accuracy of its analog-to-digital (A-to-D) converter is 0.009%+6 counts for a 5½-digit dc voltage measurement. Selectable resolution of 5½, 4½, or 3½ digits can be traded off against measurement speed. Other assemblies are available for sensing and setting digital information, switching high-level (250Vrms) devices, and for designing custom circuits to interface directly with the instrument. Up to three assemblies can be used in each 3421A mainframe.

An important feature is the instrument's ability to operate on battery power. A lead-acid battery inside the instrument is kept fully charged during normal operation on ac line power. Should ac line power be interrupted to the unit, the battery will supply power for continued operation. The 3421A can also be used in the field away from ac line power, its battery eliminating the need and expense of a portable generator. The instrument responds to the HP-IL standby command which puts the instrument into a sleep mode to conserve battery power. The 3421A can operate up to two months in the sleep mode, waking up occasionally to take measurements, or up to twelve hours continuously on its internal battery.

The design objectives for the 3421A were focused on providing transducer-based measurement capability with low cost, low power and battery backup, portability, and ease of use.

HP offers data acquisition systems based on desktop computers capable of handling a very large number of measurement points. However, until the 3421A, no similar system existed that could take full advantage of the new serial HP-IL and the low-cost controllers made available by it.

Key Features

The function and feature sets of the 3421A allow most of the transducer-based measurements needed in data acquisition and logging. Many transducers, such as thermocouples, have dc voltage outputs. The 3421A has the same 300,000-count autoranging A-to-D converter used in the 3468A and 3478A voltmeters (see article on page 3). The lowest range has the 1-μV sensitivity required for thermocouple measurements. The highest range allows a maximum input of 300 volts, giving the 3421A a wide dynamic input range. A temperature sensor on each 10-channel multiplexer card provides a reference junction for thermocouple-based temperature measurements. The type-T thermocouple conversion in the 3421A provides temperature readings directly in degrees Celsius.

The 3421A also performs resistance measurements, useful in the measurement of other types of transducers, such as RTDs (resistance-temperature detectors) and thermistors. The lowest range has a sensitivity of 1 mΩ and the highest range has a maximum input of 30 megohms. The multiplexer cards can be configured for either two- or four-wire resistance measurements. An internal zero-crossing counter allows frequency measurements (up to 10 kHz), useful for transducers with pulse outputs, such as flowmeters. Another function in the 3421A is an average-responding ac converter for measuring line-related and ac signals of frequencies up to 1.5 kHz.

All of the functions and ranges of the 3421A are electronically calibrated by the same technique used in the 3468A (see page 5). A nonvolatile CMOS RAM powered by a lithium battery is used to store all of the constants obtained during calibration of the instrument. There are separate constants for offset correction of each of the reference-junction temperature sensors. The calibration RAM is protected from accidental alteration by requiring a hardware-enable switch on the back panel (see Fig. 2) to be set for calibration. The calibration constants can also be read or written to by an HP-IL controller through the instrument's I/O interface.

The 3421A can be programmed to scan a sequence of up to 30 channels. The instrument has enough internal memory to store one scan sequence program and one set of readings. One trigger command will take readings per the specified scan sequence and store them. By using the scan commands, a set of readings can be taken, stored, and later read back into the controller. In this manner, I/O time is not required between each reading.

The scanner/multiplexer capability of the 3421A resides on up to three optional printed circuit boards accessible through removable covers on the rear panel. Each board comes with removable printed circuit board edge connectors for convenient termination of the user's field wiring. Terminations may be made permanent by purchasing extra

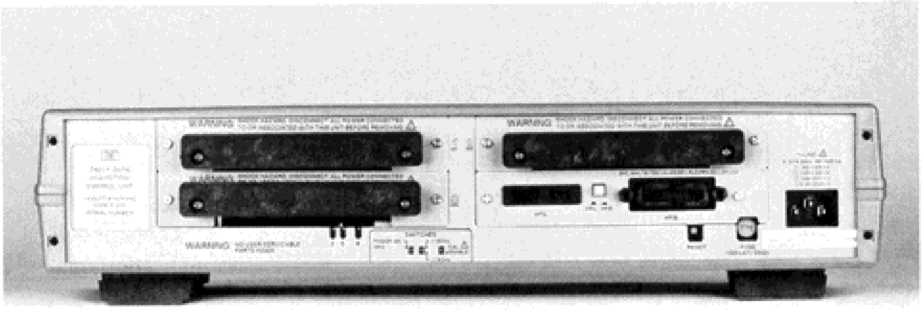

Fig. 2. *Back panel of the 3421A. The three slots can be used to insert 10-channel latching-relay cards, digital I/O cards, or breadboard cards customized by the user for specific applications. This 3421A also has the optional HP-IB interface.*

terminal blocks.

Three different plug-in assembly options exist, any of which can be placed in any or all of the three slots. These include the 10-channel relay multiplexer/actuator, a digital I/O interface, and a breadboard option.

Multiplexer/Actuator Assemblies

Each 10-channel multiplexer/actuator board contains ten latching, low-thermal-dissipation, armature relays giving the 3421A a maximum capacity of thirty relays when three boards are installed. Latching relays were chosen because of the small drain on the battery and their inherently low thermal dissipation. The ten relays can be configured by jumpers in a number of ways to suit the needs of the user. Two of the relays can be used as either two-ampere actuators or multiplexer relays. The other eight are always multiplexers, but series and/or shunt elements can be added to them. One channel comes with a removable 10:1 divider intended for use in monitoring power-line voltage, using the 3421A's internal 30Vac range. The board also can be jumper-selected to multiplex the sense terminals for four-wire resistance measurements. The **HI** and **LO** front-panel terminals are connected to the multiplexer's common bus. This bus can be disconnected from the 3421A's internal multimeter to use external instruments or to allow single-ended scanning of up to 56 points with a common ground.

Digital I/O Assembly

The digital I/O board has eight floating inputs and eight floating outputs. The inputs are protected by optoisolators. Because each input can detect the presence or absence of current flowing, either 5-volt TTL or 24-volt CMOS signals will trigger the input equally well. Each bit can be read individually, or the eight bits can be read as one word. The 3421A can be set up to trigger a multiplexer board scan sequence when a specific digital word occurs at the inputs of a digital I/O board. The outputs of the digital I/O board are protected against shorting and use isolated DMOS FET switches. An on switch is capable of sinking up to 300 mA at less than two ohms. An off switch has an impedance greater than 10 MΩ. These switches are used as open-drain outputs. Each switch can be written to individually or all eight can be written to as one word.

Breadboard Option

The breadboard option has circuitry for decoding the instrument's backplane and an area for the user to add custom circuitry. For example, this card could be configured as a multiple-channel, continuously sampling totalizer card to monitor a few channels of pulsed outputs.

HP-IB Option

To fit into more traditional instrumentation systems, the 3421A has an optional HP-IB (IEEE 488) interface. The HP-IB option does an internal conversion to the HP-IL. The internal HP-IL interface is used for isolation between the HP-IB and the user's measurement potential. A pushbutton on the rear panel (see Fig. 2) is used to select between HP-IL and HP-IB operation.

Low-Cost Design

Keeping the cost low while keeping the capabilities high was a major goal for the design team. One of the largest cost savings is realized through the mechanical packaging. Since the instrument is intended to be low-power and lightweight, plastic packaging fits the definition perfectly. The package is a two-piece full-rack-width clamshell with separate plastic front and rear panels.

The 3421A is designed to be used with a controller, so it was not necessary to include costly front-panel controls for manual operation. Front-panel-emulation programs for user convenience in setting up data acquisition applications are available for both the HP-85 Personal Computer and the HP-41 Handheld Computers. The programming for the HP-41 is achieved by adding a special ROM and keyboard overlays (see article on page 16). For use with the HP-85, the 3056DL system was developed (see box on page 13).

The block diagram of the 3421A (Fig. 3) illustrates other cost savings. Since most pulse output transducers do not use frequencies higher than 10 kHz, and ac voltage measurement at other than line frequencies is normally not done in data acquisition, the dc front end can also be used for both ac voltage and frequency counter measurements. All the protection and signal amplitude conditioning already exist in the dc front end. The additional circuitry required for ac measurements and the counter is minimal. The 3421A's microprocessor accumulates the pulses for the counter.

Another major area of cost savings is in the power supplies. Portability, and therefore battery power, was one of the major design goals. By optimizing the power

Data Acquisition and Control Software for the 3421A Using the HP-85 Computer

by David F. Leonard

To simplify the use of the 3421A Data Acquisition/Control Unit for data logging applications, the 3056DL System is available. One or two 3421As and an HP-85 Personal Computer to control them are housed in one cabinet (Fig. 1) and supplied with an appropriate package of software routines.

Most dedicated data loggers are self-contained units with the analog front end and the digital user interface portion housed in one box. Because of the low cost and flexibility of both the 3421A and the HP-85, the total 3056DL system is comparable in price to that of most single-box data loggers and is more versatile. The 3056DL software has been written to make the system easy to use for the person who is not familiar with computers or instrumentation. Thus, a user can take advantage of the flexibility of the computer without paying the price of the long startup times for which computer-based data acquisition systems have been known.

The 3056DL software package includes a data logger routine, a program that emulates an instrument front panel, instrument diagnostic programs, and graphics programs to plot data from the data logging results. Subprograms that linearize temperature transducers are also available on the tape for the user who needs to write a more specialized program.

Data Logging Setup

The data logger setup is divided into two major parts: channel setup and timing setup. A setup is done for up to 20 groups. A group is defined as a group of channels with the same label, function, data conversion equation, and limits.

A label can be up to 26 characters long. The function can be one of the following:

- dc volts
- ac volts
- Ohms (two or four wire)
- Frequency
- Thermistor temperature measurement
- RTD temperature measurement
- Thermocouple type J,K,T,E,R, or S temperature measurement
- Digital input
- 4-to-20-mA input
- Close or open an actuator or digital channel.

Data conversion software will convert inputs according to linear or fifth-order polynomial equations, or for greater flexibility, the data logger will call a subprogram (the name of which is entered during setup) at the time data conversion is done. The user writes the subprogram and stores it on the software tape. Units for the converted data can be specified. These units can be up to five characters long.

Limits are used to initiate an action when a reading or converted reading reaches a value specified by the user. Limits can be one of three types: high, low, or delta. The action will be initiated when

```
SELECT LIMIT ACTION

OpnChn =OPEN ACTUATOR/CLEAR
          DIGITAL CHANNEL
ClsChn =CLOSE ACTUATOR/SET
          DIGITAL CHANNEL
DeactGr=DEACTIVATE GROUP
Act Gr =ACTIVATE GROUP
DspWarn=DISPLAY WARNING
PrWarn =PRINT WARNING



--------------------------------
OpnChn   DeactGr   DspWarn
ClsChn   Act Gr    PrWarn     Beep
```

Fig. 2. *Limit display for the 3056DL system.*

Fig. 1. *A powerful, compact, yet low-cost data acquisition system, the HP 3056DL, is formed by combining one or more 3421As with an HP-85 Computer.*

```
GROUP NUMBER 1
LABEL:FURNACE TEMPERATURE
FIRST CHANNEL: 2
LAST  CHANNEL: 19
FUNCTION: THERMOCOUPLE-R
CONVERSION TYPE: NONE
LIMIT# 1 LOW 1000
LIMIT# 2 HIGH 1390
LIMIT# 3 NONE
LIMIT# 4 NONE
LIMIT# 5 NONE


--------------------------------
clear                    /|\      |
EDIT       DONE           |      \|/
```

Fig. 3. *Channel setup display for the 3056DL system.*

```
CHANNEL:5

FUNCTION:TC-R Deg C

READING:38.89       ▒



--------------------------------
RESET    CHANNEL DIGITAL  done
FUNCTION FORWARD REVERSE  CMD
```

Fig. 4. *Basic front-panel display on the HP-85 Computer for the 3056DL system.*

```
CHANNEL|20|21|22|23|24|25|26|27|
INPUT  | 1| 1| 1| 0| 1| 1| 1| 0|
DECIMAL VALUE OF INPUT IS 119

K1-VIEW NEXT DIGITAL CARD

K2-OUTPUT TO DIGITAL CARD

K4-RETURN TO FRONT PANEL MENU


--------------------------------
NEXT    OUTPUT           RETURN
```

Fig. 5. *Digital card display for the 3056DL system.*

a high limit is exceeded, the reading is less than a low limit, or a reading exceeds the last reading for that channel by a specified amount (delta limit). The limit actions are indicated on the HP-85's display as shown in Fig. 2. Up to five limits can be specified per group.

Fig. 3 shows the channel setup display. Specifications for the channel setup are entered by moving the line (shown under limit #1 in Fig. 3) to the line that is to be changed. The line is moved up and down by pressing the softkeys labeled by arrows. When the EDIT key is pressed, the display instructs the user on what entries can be made, usually by relabeling the softkeys. After the entry is made, the CRT returns to the original display, which then shows the entry just made.

Once the channel setup is complete, the timing setup for each group is done. The timing setup specifies whether or not the group of channels is to be scanned at specified intervals or at a time of day, the number of times the group is to be scanned, and finally how the resulting data is to be handled. Data can be stored on tape, displayed on the HP-85's CRT, or printed on its printer.

Front-Panel Emulator

The basic front-panel display is shown in Fig. 4. The first line shows the acquisition channel that is closed. The function is shown on the second line. The third line shows the last reading read from the 3421A. The shaded rectangle, shown to the right of the reading, blinks when a new reading is displayed.

- When the FORWARD or REVERSE softkey is pressed, the 3421A will step forward or backward through the acquisition channels. The reading shown will then reflect the input on the new channel chosen.
- The CHANNEL softkey allows the user to close or open an acquisition, actuator, or digital channel.
- When the FUNCTION softkey is pressed, the user can change the function to one of the fifteen available.
- The CMD softkey is used for outputting an ASCII command to the 3421A.
- When the DIGITAL softkey is pressed and a digital card is present in the 3421A, the display shown in Fig. 5 appears. Here the display shows the eight-bit input of a digital card in slot 2. When the OUTPUT softkey is pressed, the display prompts the user for a decimal number to be output to the digital card, and the 3421A's liquid-crystal display shows the value of the digital outputs.

David F. Leonard

Dave Leonard received his BSEE degree from the University of Colorado in 1978 and began working at HP that year. He worked on the 3497A Data Acquisition Unit before joining the 3421A and 3056DL design teams. In his spare time, he is working on an MSEE degree at Colorado State University. He is married, has two children, and lives in Westminster, Colorado.

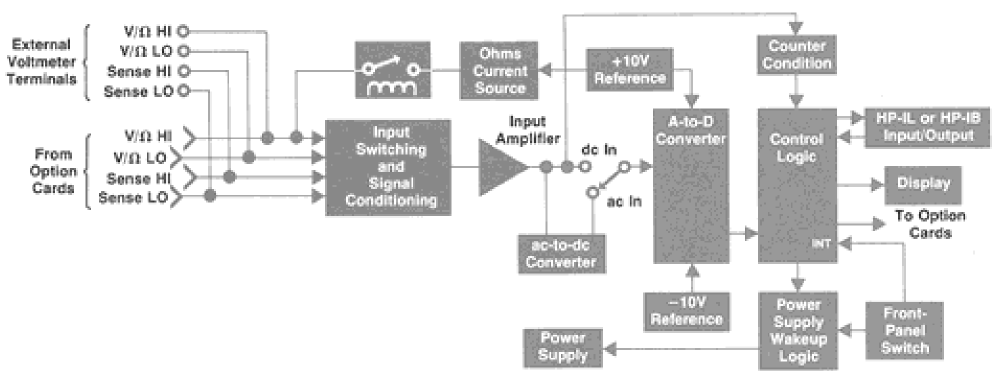

Fig. 3. *Block diagram of the 3421A.*

Table I
3421A Instruction Set

Standard Instruction Set:

DCV	dc volts [channel list]
ACV	ac volts [channel list]
TWO	Two-wire ohms [channel list]
FWO	Four-wire ohms [channel list]
TEM	Temperature [channel list]
FRQ	Frequency [channel list]
TOT	Totalize [channel number]
REF	Reference junction temperature [channel number]
CLS	Close a single channel or digital bit ⟨channel number⟩
CLP	Close a pair of scanner channels ⟨channel number⟩
OPN	Open a channel or digital bit [channel number]
WRT	Write a digital byte ⟨slot number, decimal value 0-255⟩
RED	Read a digital byte ⟨slot number⟩
BIT	Read a digital bit ⟨bit list⟩

Advanced Instruction Set:

RS	Reset
F	Function ⟨function number⟩
R	Range ⟨range exponent⟩
RA	Range auto ⟨1 if on, 0 if off⟩
G	Gate time ⟨second exponent⟩
N	Number of digits of resolution ⟨3,4, or 5⟩
T	Trigger mode ⟨number⟩
Z	Autozero ⟨0 if off, 1 if on⟩
C	Calibrate [cal value]
SR	Status registers
DN	Display number [number 0-29]
DI	Display digital inputs
DO	Display digital outputs
M	SRQ mask [number]
DT	Digital trigger ⟨digital channel⟩
RL	Read channel list
LS	Load single scanner channels into list ⟨channel list⟩
LP	Load pairs of scanner channels into list ⟨channel list⟩
SI	Scanner increment ⟨0 or 1⟩
UC	Unconditional close ⟨channel number⟩
MH	Monitor high ⟨digital bit⟩
ML	Monitor low ⟨digital bit⟩
AN	AND mask [decimal value 0-255]
XR	XOR mask [decimal value 0-255]
MN	Monitor ⟨slot number⟩, used with **AN** and **XR**
DS	Digital set ⟨slot number, decimal value 0-255⟩
DC	Digital clear ⟨slot number, decimal value 0-255⟩
CAL	Calibration RAM ⟨1 if read, 2 if write⟩

[ ] if optional
⟨ ⟩ if not optional

supplies, knowing that a battery will be always present, a significant savings is realized over traditional battery options in other instruments that use more expensive center-tapped transformers and linear regulators for direct ac operation in addition to battery-powered supplies like those used in the 3421A.

Instrument Friendliness

Our ability to use instruments in systems has taken gigantic steps since the first programmable instrumentation was introduced in the 1960s. We feel that because of its low cost and high capability, the 3421A will find its way into the hands of some less electronically sophisticated users. Therefore, we made it easy to program. The first major hurdle in programming most instruments is remembering to write to the instrument everything it needs to know to complete the task. The 3421A's standard instruction set (see Table I) includes most of the normal measurement tasks made by an instrument of this type. By sending it just one simple command, everything is handled by the instrument to complete the entire task. For example, to measure dc voltages on channels 2, 3, 4, and 8, the user merely sends DCV2-4,8 or DCV2,3,4,8,. If this instruction is compared to those for earlier instruments capable of making the same set of measurements, it can be seen that the 3421A is much easier to use. The 3421A also contains more traditional instructions which we have chosen to call the advanced instruction set. To take the same set of readings using the advanced instructions, the following commands are sent to the 3421A:

LS2,3,4,8	(Loads scanner list)
F1RA1Z1N5T3	(Configures 3421A; F1=dc volts, RA1=autorange, Z1=autozero, N5=5 digits, T3=trigger through scanner list)

Besides the software programs available for the HP-41 and HP-85 controllers, other features include an internal type-T thermocouple conversion. Thermocouple measurement with the 3421A is easily accomplished by connecting the thermocouple to the appropriate channel and sending TEM(channel number). The measurement reads the temperature of the reference junction and the voltage across the thermocouple. A software compensation is performed on these readings to give the corrected temperature. A test of friendliness devised early in the definition phase of the project centered around how easily a temperature measurement could be made using a thermocouple. For most instruments, it is a complicated task. However, with the 3421A, all the work is done for the user.

Low-Power Operation

To do a good job at remote data logging and to make full use of the battery, low-power design techniques are used throughout the instrument. One of the major power savings is realized through the use of latching relays in both the A-to-D front end and in the multiplexer. Each relay is magnetically latched either on or off; all that is required to set or reset a relay is a 10-ms current pulse through the appropriate winding. An additional advantage of these relays is the low thermal voltage offsets because of the lack of power dissipation.

Another major contributor to keeping the power consumption low is the power supply design. The ac line input charges the battery, and the ±15-volt supplies are derived using an efficient switching technique. The 5-volt supply is linearly regulated directly from the battery. The liquid-crystal display and extensive use of CMOS logic also contribute to reducing power consumption.

Implementation of the HP-IL power-down mode provides the user with greatly increased battery life. In this sleep mode, only a small fraction of the circuit is kept powered up. At times specified by the user, the HP-IL system can wake up and perform its function. For example, in continuous operation, the battery life of the 3421A is specified at twelve hours minimum. Use of the HP-IL power-down function extends the battery lifetime, allowing the user to take a set of thirty readings once an hour for a period of more than one month. Since the HP-41, the 82162A Printer, and the 82161A Cassette Drive also implement the power-down function, a powerful battery-powered system, which can be controlled by the 82182A Time Module (which plugs into the HP-41), can be assembled for unattended data logging.

Acknowledgments

The author wishes to acknowledge the following persons for their contributions to the design of the product. Chuck Clark, multiplexer, digital I/O and breadboard options, Rob Leiby, strife testing, Dave Leonard, power supplies and 3056DL software, Rob Saffer, packaging and mechanical design, Vicky Sweetser, logic and firmware, Kevin Thompson, HP-41 ROM, Dave Wolpert, HP-IB and HP-41 ROM, and Paul Worrell, A-to-D converter and signal conditioner.

James J. Ressmeyer

Jim Ressmeyer was born in Pipestone, Minnesota and attended the University of Minnesota, receiving the BSEE degree in 1972. Jim came to HP in that same year and has worked on thin-film hybrids and analog design for voltmeters, including the 3456A. He was responsible for the ohms, input filter, and front-end switching sections in the 3456A and now serves as a project manager on the 3421A and 3056DL. Between work and outside activities, he attended Colorado State University, earning an MSEE degree in 1975. He and his wife and two daughters live in Loveland, Colorado. Jim enjoys bowhunting, playing racquetball, and backpacking and camping with his family.

Low-Cost Instrument Control: A New ROM for the HP-41 Handheld Computers

by David L. Wolpert

HP'S NEW SERIAL INTERFACE LOOP (HP-IL) and 82160A HP-IL Module make it possible for an HP-41 user to control instruments such as the 3468A Multimeter and 3421A Data Acquisition/Control Unit, thus forming low-cost measurement systems for bench or field applications. To reduce the amount of programming and simplify use, a custom ROM and keyboard overlays (Fig. 1) are available for HP-41 users. The HP 44468A Data Acquisition and Control Package (DA/C Pac) is based on the instruction set for the 3421A. Each of these instructions performs a complete measurement task or a complete operation.

To illustrate the capability and friendliness provided by the 44468A DA/C Pac ROM, consider the measurement of ac voltage by a 3468A Multimeter on the loop. Even without DA/C Pac ROM, this can be done by a fairly simple program for the HP-41:

```
01*LBL "MEAS2"
02 "HP3468A"
03 FINDID
04 SELECT
05 "F2N5RAZ1T2"
06 OUTA
07 IND
08 END
```

The above program finds the voltmeter's address on the loop, selects it, sets function, range and trigger, and takes a reading. But if there is no 3468A on the loop, there will be an address error at step 04 (ADR ERR), and if a syntax error is noted by the 3468A, step 07 may produce a TRANSMIT ERR. To trap most of these likely errors, a more complex program is necessary. The following example handles most foreseen anomalies, and responds with friendly prompts on the HP-41's display such as NO INST (no such instrument found) and INST ERR (instrument error).

```
01*LBL "ACV"
02 "HP3421A"      ← First look for a 3421A. The ROM actually looks for a measurement device, using accessory poll.
03 FINDID
04 X=0?
05 GTO "F68"
06 SELECT         ← Tells the interface which device to talk/listen to.
07 "ACV"          ← This is the standard 3421A instruction for measuring ac voltage.
08 OUTA
09 INSTAT         ← Read instrument status byte.
```

```
10 FS? 05          Error occurred if flag 5 is set in status byte.
11 GTO "ER2"
12 IND             Get the reading.
13 RET
14*LBL "F68"       No standard instruction set instrument was found, look for a 3468A.
15 "HP3468A"
16 FINDID
17 X=0?
18 GTO "ER1"
19 SELECT          This is the 3468A instruction string for a single ac voltage reading.
20 "F2N5RAZ1T2"
21 OUTA
22 IND             Get the reading.
23 RET
24*LBL "ER1"
25 "NO INST"       3421A or 3468A not found—cannot measure ac voltage.
26 AVIEW
27 STOP
28 *LBL "ER2"
29 "INST ERROR"    Syntax or calibration or other error.
30 AVIEW
31 STOP
32 END
```

By contrast, the 44468A DA/C PAC ROM reduces this program to three simple lines:

```
01*LBL "MEASURE"
02 ACV
03 END
```

This trivial program returns an ac voltage to the HP-41's X register, and handles all the commands that are necessary for using the 3421A or 3468A.

DA/C Pac ROM

The custom ROM is divided into seven basic parts:

- Microcode for friendly operation of instruments. This makes it easy to use the automatic addressing features of the HP-41 and HP-IL. Included are some basic instrument operations for digital multimeters, scanners, and combination devices such as the 3421A. These include MEASURE dc VOLTAGE, CLOSE CHANNEL, et cetera.
- Microcode for polynomial (and other) expansions of temperature functions. This makes the HP-41 significantly faster in performing temperature conversions, a typical user task for the 3421A and other instrument systems. Conversion functions for thermocouples (T,J,R,E,K, and S types), thermistors (2252 or 5000 ohms at 25°C), and platinum resistance-temperature detectors (RTD, 100 ohms at 0°C) are included, with software cold-junction compensation for the thermocouples.
- User code for complete temperature measurements, including cold-junction measurement and software compensation.
- A data logger application program. This simple data acquisition program can print or store on an 82161A Digital Cassette Drive the data from up to 30 channels of inputs of various kinds (voltage, resistance, temperature, frequency) taken at time intervals specified by the user during setup.
- Front-panel program to allow the HP-41 to manipulate the 3421A, acting as its front panel.
- Miscellaneous routines which include an alarm setup program (prompting), a routine to find an instrument, DVM or scanner on the HP-IL, a routine to output a command to an instrument, and a decode routine to return measurement functions and units to the data logger.

Fig. 1. *The 44468A Data Acquisition/Control Package ROM comes with overlays for the HP-41 keyboard to simplify HP-IL measurement system programming.*

- Miscellaneous microcode for easy programming, such as a key assignment routine and programmable timer alarm clearing.

Because there are certain things that cannot be done by the standard HP-41 instruction set, the DA/C Pac ROM extends the instruction set by microcode to use the Accessory ID provisions of the HP-IL. Also, the thermocouple/thermistor/RTD conversions are written in microcode. Although these could have been done with standard HP-41 instructions, the microcode executes much faster and does not require the use of the stack or other registers. Below is a listing of some microcode routines in the measurement portion of the DA/C Pac ROM:

DCV	Measure dc voltage
ACV	Measure ac voltage
TWO	Measure resistance (two-wire)
FWO	Measure resistance (four-wire)

These four commands differ only in the string that is sent to the measurement device. The command flow is as follows, where (cr) indicates a carriage return and (lf) indicates a line feed operation.

1. Search for measurement device (detector)
   A. If instrument type 51 (e.g., 3421A) is found:
      a. Address device to listen
      b. DCV: send "DCV (cr) (lf)"
         ACV: send "ACV (cr) (lf)"
         TWO: send "TWO (cr) (lf)"
         FWO: send "FWO (cr) (lf)"
   B. If 3468A is found:
      a. Address device to listen
      b. DCV: send "F1N5RAZ1T2 (cr) (lf)"
         ACV: send "F2N5RAZ1T2 (cr) (lf)"
         TWO: send "F3N5RAZ1T2 (cr) (lf)"
         FWO: send "F4N5RAZ1T2 (cr) (lf)"
   C. If instruments are not found:
      a. Display "NO INST"
      b. Return
2. Get device status byte
   A. If bit 5 is set:
      a. Display "INST ERR"
      b. Return
   B. If bit 5 is clear:
      a. Input device data to X register
      b. Return

Some examples of the mathematical routines available in the DA/C Pac ROM are listed in Table I.

The 3421A front-panel program is another part of the DA/C Pac ROM; it makes it very easy to set up and test a 3421A. It prompts the user when numeric input is required and uses standard instructions to address the 3421A. For example, the user can connect the HP-IL cables, turn on the 3421A and the HP-41, and execute the following.

HP-41 Keys	Display	Comment
Xeq, Alpha, F, P, Alpha		The HP-41 will find and select the 3421A on the HP-IL and reset it.
DCV		This is the **Σ+** key if the DA/C Pac ROM overlay (Fig. 1) is not in place.
	Channel?	The HP-41 prompts the user for a channel number. The user would then put in the channel number and press **R/S**, or press **R/S** alone to measure the current channel or at the front-panel terminals.
2, R/S		The user has selected channel 2.
	3.00102 00	The reading from channel 2 is flashed on the display repeatedly.
FOR		The user wishes to advance to the next channel (the **SST** key without the overlay).
	−3.00105 00	The reading from channel 3 is flashed on the display repeatedly.

When an error occurs, caused by selecting a channel that is not present or an invalid function for the current channel, the calculator beeps and displays dashes to indicate that no reading is available.

Table I
Example DA/C Pac ROM Mathematical Routines

Command	Function
C-F	°C to °F conversion $X' = 1.8X + 32$
THM2	Ohms to °C, thermistor is 2252Ω at 25°C $X' = [1/(a+b \ln X + c(\ln X)^3)] - 273.15$ where a = 1.470873889E−3 b = 2.377905230E−4 c = 1.032577937E−7
THM5	Ohms to °C, thermistor is 5000Ω at 25°C $X' = [1/(a+b \ln X + c(\ln X)^3)] - 273.15$ where a = 1.285496378E−3 b = 2.360998857E−4 c = 9.324409398E−8
RTD	Ohms to °C, RTD is 100Ω at 0°C If $X<100$: $X' = a + bX/10^2 + cX^2/10^4 + dX^3/10^6$ where a = −241.9967592 b = 222.5606179 c = 25.24882388 d = −5.812682625 If $X \geq 100$: $X' = a - \sqrt{b + cX/100}$ where a = 3367.821441 b = 13,065,764.86 c = −1,723,543.606

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   HP 3421A
DATA LOGGER
2-3
DCV
23-25
ACV
4-5
DCV
RECORD OFF
PRINT

PASS 1
07/12/82 2:00 PM

2: 95.9530E-3 DCV
3: 29.9090E-3 DCV

23: 34.8000E-3 ACV
24: 35.1000E-3 ACV
25: 35.1000E-3 ACV

4: 7.74500E-3 DCV
5: -96.0940E-3 DCV

PASS 2
07/12/82 2:15 PM

2: 232.888E-3 DCV
3: 154.632E-3 DCV

23: 31.8000E-3 ACV
24: 31.8000E-3 ACV
25: 31.7000E-3 ACV

4: 96.7520E-3 DCV
5: -8.97100E-3 DCV
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Fig. 2. *Typical data logging printout using the 44468A DA/C Pac in an HP-41CV Handheld Computer controlling a 3421A Data Acquisition/Control Unit and an 82162A Printer. Program records dc voltages on channels 2 and 3, ac voltages on channels 23, 24, and 25, and dc voltages on channels 4 and 5 during each periodic scan sequence. The values recorded for two scans are shown.*

The data logger program is also very simple to use, yet has some powerful capabilities not usually found in such a small system. The user is guided through a setup in which the user can select channel groups and assign various functions to these groups. Functions available include six thermocouple types, dc and ac voltage, two- and four-wire resistance, RTD and thermistor measurements, frequency, user-written routines, actuator control, and digital outputs. The user is prompted to find out whether the readings are to be recorded on the 82161A Digital Cassette Drive or printed on the 82162A Thermal Printer. Next the user is asked to select a start time, a time interval for the measurements, and the number of scans to be done. Between each scan of the channels, a loop power-down command (PWRDN) is used to conserve battery life, in case of a system which is operated away from ac line power. At the proper time, the HP-41 and the HP-IL devices are powered up and a measurement cycle is performed, with the results being printed and/or recorded as specified by the user before the system is powered down to await the next scan. Fig. 2 shows a typical data logging printout.

Fig. 3 illustrates the use of the 44468A DA/C Pac ROM in an HP-41 to control a 3468A Multimeter for dc voltage measurements in the field.

Fig. 3. *Measuring electrical parameters in the field is now much easier using a 3468A Multimeter, an HP-41 Handheld Computer, and the 44468A DA/C Pac ROM.*

David L. Wolpert

Dave Wolpert has been with HP since graduating from the Georgia Institute of Technology in 1972 with a BEE degree. He started in data acquisition on the design team for the 3495A Scanner, was responsible for the digital control portion of the 3467A Logging Multimeter, and after a stint in production engineering, worked on the 3497A Data Acquisition/Control Unit and the 3054DL system. Dave was responsible for coding the temperature conversion and binary/decimal routines in the 3421A and implementing the HP-IB interface board. He is currently on loan to an HP group investigating code and format standards for programmable instruments. His outside interests include music and enjoying the Colorado outdoors.