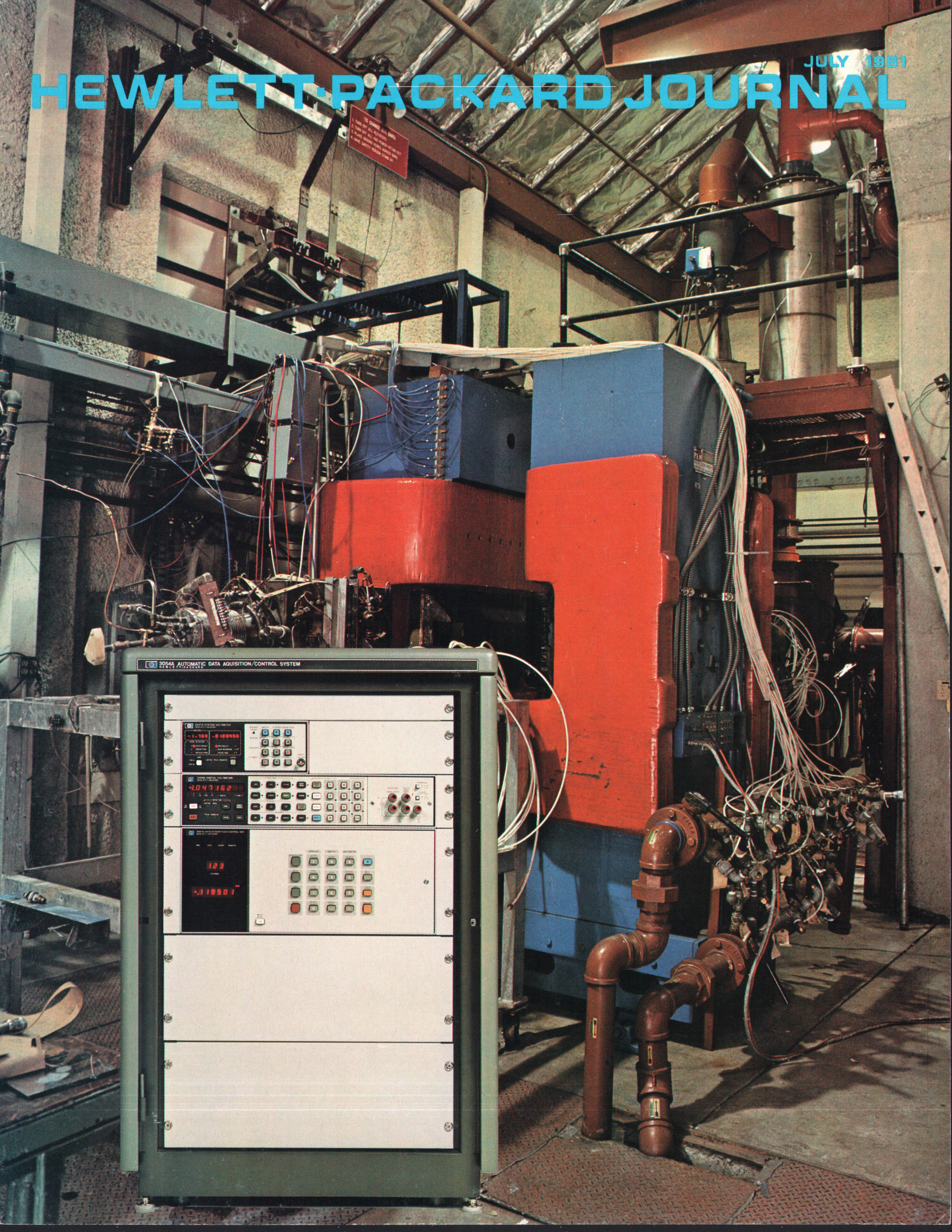
JULY 1981

HEWLETT-PACKARD JOURNAL



HEWLETT·PACKARD JOURNAL

Technical Information from the Laboratories of Hewlett-Packard Company

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JULY 1981 Volume 32 • Number 7

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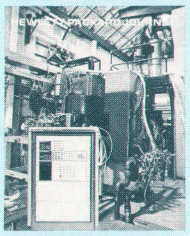

Aircraft design, pollution monitoring, engine development, forest management, agricultural yield studies, and solar system management are about as diverse in appearance and effect as they can be, but these and many other industrial activities have an important common requirement, a need for data acquisition and control. In all of these applications, data is gathered to see how things are going, and depending on the results, controls are applied or adjusted. Data may be acquired by making measurements on sensors such as flow meters, thermocouples, load cells, strain gauges, and clocks. Controls may be applied by means of valves, heaters, and relays. These days there's often a computer in the middle of things, analyzing the data and automatically adjusting the controls.

The articles in this issue describe some new Hewlett-Packard products for precision data acquisition and control. A basic product is Model 3497A Data Acquisition/Control Unit (pages 9 and 16), a precision scanner with built-in measurement and control capabilities. It's designed to operate under computer control, and it's available with a variety of input and output options so that each user can put together a system that's just right. You can also get the 3497A in a system that includes an HP computer and a pair of high-performance voltmeters. The 3054A/C/DL Data Acquisition/Control Systems (page 3) come with special software and are ready to start solving problems as soon as they're delivered. Our cover depicts a 3054A application—monitoring and control of magnetohydrodynamic (MHD) power generation experiments. Our thanks to the Stanford University Mechanical Engineering Department for letting us take the background photograph in their High-Temperature Gasdynamics Laboratory.

An important consideration for anyone designing a computer-controlled system is what kind of computer goes into it. If the system is going to be mass-produced, a bare-bones, single-board computer or microcomputer offers the lowest unit cost, but may require a large investment in software development. A desktop computer is much friendlier, comes with a good deal of software, and is relatively easy to develop applications software for, but costs more and has features that probably aren't needed or wanted in a system designed for use by non-programmers. (Some people have bolted sheet metal over desktop computers' keyboards so the system operators can't get at the keys). A way out of this dilemma is offered by Model 9915A Computer (page 23). Basically a desktop computer without the features that aren't needed for systems applications, it lets you develop software on a friendly desktop computer—the HP-85 Personal Computer—and then just plug it into the 9915A.

-R. P. Dolan

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Instrument System Provides Precision Measurement and Control Capabilities

Measurement and control instruments are integrated in a system package designed for easy use in data acquisition and control situations. This system is supported by software for common monitoring and actuating applications.

by Virgil L. Laing

EVER SINCE THE ADVENT of the HP Interface Bus (HP-IB*), scientists and engineers have been able to assemble systems of highly capable instruments under control of a general-purpose computer to implement automatic, user-defined solutions of test, measurement, and control problems. Examples include multichannel weather monitoring, digitizing transient waveforms from transducers, production test of fractional horsepower motors, and energy management of entire buildings. The computer provides the user-specified test and measurement procedures, control algorithms, and data analysis capability and the instruments are the eyes and ears of the computer. As the automation task grows and changes over a period of time, the user simply changes the test program to set new pass/fail limits, alter scan sequences, or implement new data input/output formats. Because the user selects and controls the operations for the test program, the user is not restricted by a dedicated hardware solution or a program that is difficult to understand or change.

A new HP-IB-based system designed for this type of service, Model 3054A Automatic Data Acquisition/Control System (Fig. 1), combines precision measurement and control capability, software for commonly encountered tasks (e.g., thermocouple conversion), factory integration of the instruments in several system packages, and detailed documentation and system performance specifications.

The system consists of HP's new 3497A Data Acquisition/Control Unit (see article, page 9), 3456A Digital Voltmeter,[1] and 3437A System Voltmeter with one of several HP computers—HP-85A, 9825T, 9835A or 9845T—in a number of package options. The software supplied with the system—either BASIC or HPL—is quite substantial—8000 lines total—and consists of three types: subprograms called from the user-written mainline test program, verification and diagnostic programs to verify the operational integrity of the instruments, and application programs that provide complete ready-to-run routines to help the user get the system operating and doing useful work the day it is received. The application programs also provide tutorial examples of how to attack a data acquisition problem and get optimal performance from the system.

The total system error is specified fully (including DVM accuracy, switch offset voltages, conformity of the conversion expression to standards, self-heating effects, and thermal gradients in the reference junction assembly). The user knows the maximum error in the measurement when the unknown is connected to the multiplexer terminals because the system is tested and specified as a single instrument. All the hardware and software interactions from the multiplexer input terminals to the computers are included in the specifications.

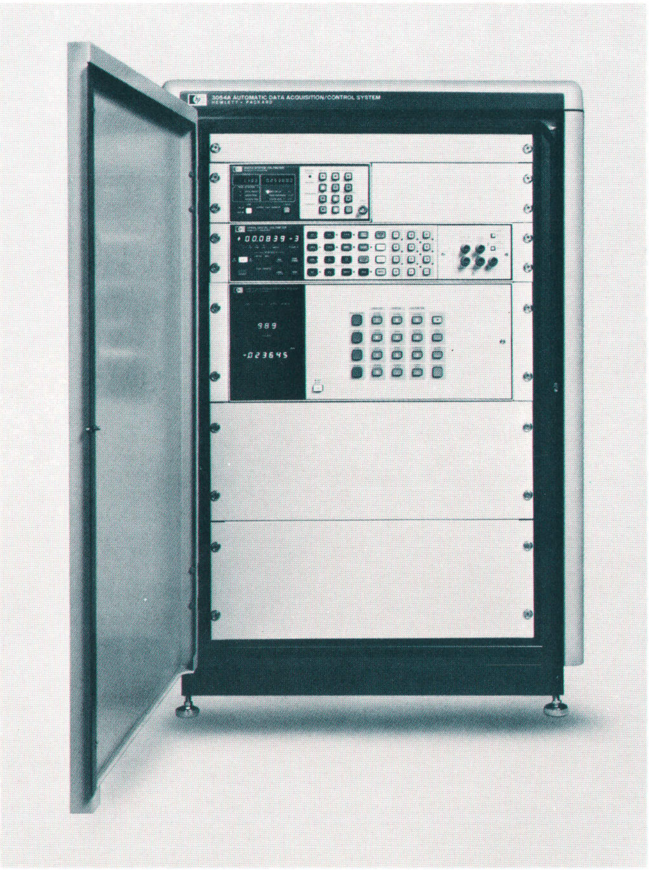

Fig. 1. *The 3054A is a computer-based automatic data acquisition and control system. The system is interfaced to any of four HP computers via the HP-IB and is complete with specialized software support.*

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*Hewlett-Packard's implementation of IEEE Standard 488 (1978).

Thermocouple Conversion and Transducer Curve Fitting

The thermocouple EMF-versus-temperature characteristics supported in the 3054A Automatic Data Acquisition/Control System are defined by the International Practical Temperature Scale, IPTS-68, as described in NBS Monograph 125. For example, in IPTS-68, the type-T thermocouple voltage-versus-temperature characteristic is specified as a 14th-degree polynomial in temperature throughout the range of −270° to 0°C. Over the range 0° to 400°C, it is specified as an 8th-degree polynomial in temperature. Thus, given any temperature from −270° to 400°C, the voltage is uniquely specified by one of these high-order polynomials.

In measuring temperature with a thermocouple, an inverse relationship expressing temperature as a function of voltage is required. IPTS-68 does not provide such a relationship. Curve-fitting techniques ranging from straight lines to high-order polynomials can be used to provide suitable approximations over various temperature ranges. Selection of an approximation technique depends on execution speed required, memory available, and accuracy of fit desired.

The technique used in the 3054A system software divides each thermocouple voltage range into eight equal-error sectors (Fig. 1) and approximates the temperature within each sector by using third-order polynomials that are continous on the sector boundaries. Thus, 32 six-digit coefficients are used to represent a thermocouple's behavior over its entire range.

In making a thermocouple temperature measurement, the 3054A system measures the output voltage, implements a three-level binary search to find the proper sector, and then evaluates the nested third-order polynomials for that sector to obtain the temperature. Typical approximation errors using this technique are 0.05°C (Fig. 2). Compared to a single higher-order polynomial approximation, the eight-segment technique requires more memory, but executes substantially faster and with lower approximation error.

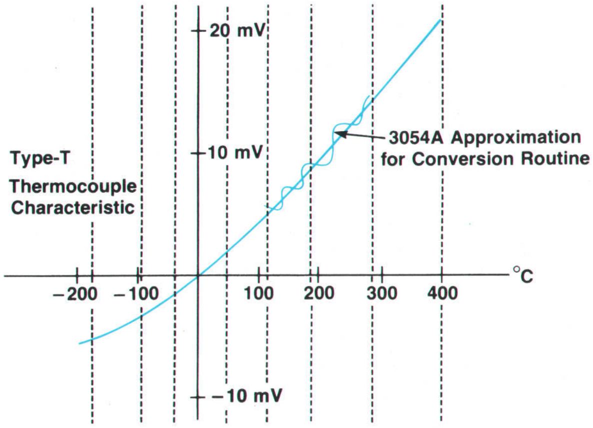


Fig. 1. *The 3054A conversion routines divide a thermocouple characteristic into eight unequal temperature intervals so that third-order polynomials can be used within each interval to approximate the curve with about equal error.*

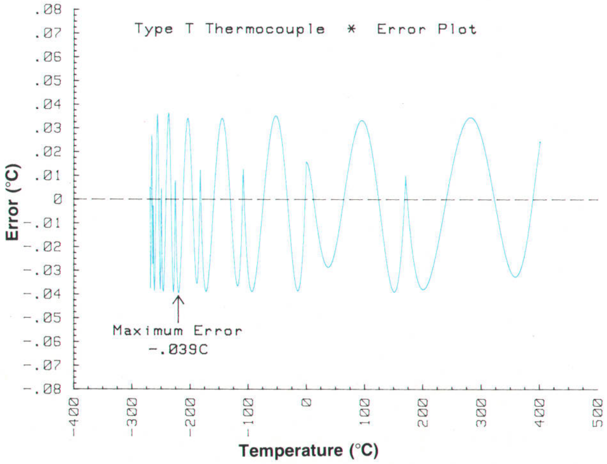


Fig. 2. *Plot of error versus temperature using the segmented third-order polynomial approximation illustrated in Fig. 1.*

Similar approximation techniques are used to represent the temperature-versus-resistance characteristics of the 100Ω platinum RTD and 2252Ω thermistor, which are also supported with ohms-to-temperature conversion software in the 3054A.

The 3054A curve-fitting application program gives the system operator a straightforward, easy-to-use way to develop closed-form analytic expressions describing the input-output characteristic of a transducer. For example, a rotating-vane flowmeter, used to measure the flow of natural gas into a building's heating plant, may be supplied with a manufacturer's calibration table containing six or ten data pairs relating gas flow to current on a 4-to-20-mA current loop. By fitting this data with an appropriate expression, a memory-efficient, rapidly executing conversion routine can be implemented.

The 3054A curve-fitting program can fit data with straight lines, polynomials, exponentials, and logarithmic curves. The conversion routines supplied for the thermistor and RTD were in fact generated using the 3054A FITTER program on a HP 9845B desktop computer. The program's ability to generate close-fitting expressions is indicated by thermistor and RTD worst-case-fit errors of 0.061°C and 0.012°C, respectively.

Subprograms

The 3054A subprograms consist of 37 instrument drivers and utility programs intended to help the user with tasks frequently encountered in data acquisition and control. They are supplied on a separate tape cassette and consist of function and subroutine subprograms. The subprograms are rather short blocks of instructions—usually 15 to 30 lines—to be called by a user's program written to do the overall task. This allows the programmer to write at a very high task-oriented level. The user need not be concerned with the details of converting millivolt dc readings to °C for a type-K thermocouple. Nor does the user have to take any special action or precautions to compensate the thermocouple measurement for the fact that the reference junction is not at ice point (0°C), which is assumed in the NBS (National Bureau of Standards) and ANSI (American National Standards Institute) thermocouple standards. The 3054A hardware and software are designed to relieve the programmer of all these details. The programmer merely calls the subprograms Hc_deg or Sc_deg and supplies the desired multiplexer channel number and thermocouple type as arguments. The temperature in °C is returned as the value of the function. Subprograms are included for all the common ANSI thermocouple types (J, K, T, E, R, S, B and the relatively new Nisil-Nicrosil thermocouple). Similar function subprograms perform ohms-to-degrees-Celsius conversions for resistive temperature transducers—the platinum RTD (resistive-temperature detector) and a standard thermistor (2252Ω at 25°C). When the RTD and thermistor functions are called, the multiplexer channel is passed as the argument. The subprogram executes a specialized autoranging resistance measurement that minimizes the self-heating error in the transducer, and evaluates a stored mathematical expression to convert the resistance reading to temperature which is returned as the function's value.

All of the subprograms contain system-level error checking that traps common programming or hardware errors such as channel numbers greater than 999, invalid thermocouple types, and instruments not responding due to inadvertent power removal. When a system error is detected, the computer's internal printer outputs a message identifying the error and the subprogram in which it occurred. Control is returned to the calling routine and the subprogram task remains uncompleted. Most important, the error will not cause the computer to terminate execution abnormally, which could be disastrous for a system performing an unattended task.

Application Programs

The application program portion of the system software consists of a set of complete, fully tested, ready-to-run programs that perform tasks frequently encountered in data acquisition, test, and control applications.

With the DATA LOGGER program, for example, the user specifies a specific task by entering the desired function, channel assignment, and timing via a menu-format data-entry process. No programming in computer language is required. After the logging is complete, the program features convenient data review and analysis capabilities. Again, the emphasis is on doing the complete data acquisition task from setup through data analysis.

FAST THERMOCOUPLE is a more specialized example of real-time programming. In many instances, simultaneous data acquisition from several channels is desired but economically unattractive. A useful compromise is reached by sequentially scanning through the desired channels in some acceptably short time. In the FAST THERMOCOUPLE programs (one for each DVM option), high-speed sampling is achieved using the 20-channel hardware-compensated thermocouple assemblies, voltmeter internal reading storage, the fast scanning capabilities of the 3497A Data Acquisition/Control Unit, and high-speed packed-mode data transfers to the system controller. The TRANSIENT CAPTURE application program illustrates similar concepts using the high-speed 3437A System Voltmeter to sample at rates in excess of 4500 samples per second.

Why Compensate Thermocouples?

Because of their low cost and rugged mechanical characteristics, thermocouples are perhaps the most widely used temperature measuring devices. Thermocouple measuring circuits always contain at least two junctions of dissimilar metals, and their output voltages are a function of the temperatures of these junctions, a situation which complicates their use in everyday applications.

The tables and equations defining thermocouple voltage as a function of temperature assume that the junction other than the measuring junction, that is, the reference junction, is at ice point (0°C). This control of the reference junction temperature can be accomplished in laboratory settings by immersing the thermocouple-to-copper junctions (nearly all measuring devices are implemented with copper input terminals) in an ice bath (Fig. 1a). Where large numbers of thermocouples are involved, it is much more convenient to connect the thermocouple wires directly to the measuring equipment.

In the situation of Fig. 1b where the reference junction is not at 0°C, the simple NBS table lookup or polynomial expression for temperature as a function of voltage cannot be used because the connection to copper at room temperature reduces the net EMF around the measurement loop.* We must compensate or correct the measured voltage for this loss. If the voltage is added electronically by including a temperature-dependent source in the measurement loop, we call this hardware compensation and the source automatically follows the temperature of the multiplexer input terminals over the range of 0° to 65°C. If the value of the compensating voltage is simply added to the measured voltage by the system controller, we call this software compensation. In either case, before executing the voltage-to-temperature conversion algorithm, the measured thermocouple voltage must be compensated for the fact that the thermocouple-to-copper junctions are not at ice point.

*For more detailed information on thermocouples and compensation, consult HP Application Note 290 "Fractional Temperature Measurements".

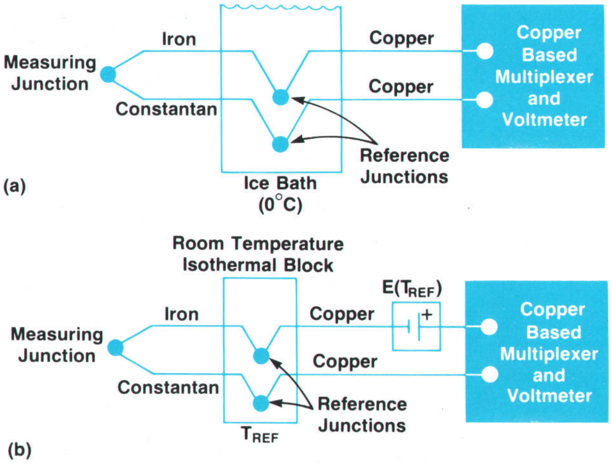


Fig. 1. *(a) Ice point compensation. The reference junctions for this type-J thermocouple are kept at 0°C by using a saturated ice bath. The temperature corresponding to the measured voltage can then be obtained directly from published thermocouple characteristic tables. (b) Automatic compensation using hardware or software methods. The type-J thermocouple's reference junctions are at temperature* T_{REF}. *The voltage* $E(T_{REF})$ *is added electronically or in software to compensate for the voltage generated by connecting the thermocouple leads to the copper terminals at a temperature other than 0°C.*

Verification Programs

The verification software allows a user to verify the operational readiness of the system controller, the HP-IB interface, and the individual instruments within the system. Used upon initial receipt of the system or when a hardware malfunction is suspected, the verification checks, while not designed to troubleshoot the individual system components, will provide information that will often be a great aid in troubleshooting. A special verification connector card (standard on 3054A and 3054C, optional on 3054DL) permits verification of individual components such as relays and optical isolators on 3497A multiplexer and digital-input option cards. In the event that a failed component such as a welded contact or open-coil relay is encountered, the software will clearly identify the component by channel number and failure symptom.

Precision Data Acquisition Teams up with Computer Power

by Lawrence E. Heyl

The HP Model 3054C Data Acquisition/Control System combines the power and flexibility of the HP 1000 Computer with HP's newest data acquisition instrumentation, and adds the convenience of a user-oriented subroutine library, factory integration of the instrumentation, and extensive system-level documentation and performance specifications. This combination couples high precision measurement and control capability with the advantages of multiple development languages, a multi-user environment, powerful networking capability, and access to the extensive line of HP peripherals.

The 3054C consists of a 3497A Data Acquisition/Control Unit with real-time clock, HP-IB interface, and optional 5½-digit DVM and current source, a 3456A Digital Voltmeter (6½-digit DVM), system software on either tape cartridges or flexible disc, and system documentation. An HP 1000 M,E,F or L-Series Computer is used as the system controller and provides for data and file storage and program development, all in the real-time, multi-user environment of the HP RTE operating system.

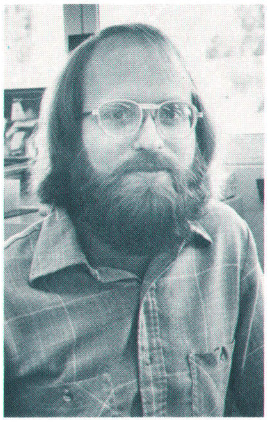
The system software for the 3054C includes a subprogram library, verification programs, and utility routines totaling over 5000 lines of source code. Subprograms may be called from FORTRAN, Assembly, PASCAL, or BASIC programs. The use of these prewritten subprograms provides a higher-level approach to writing application software, allowing the user to concentrate on the solution to a problem rather than the details of instrument syntax and operation. Program development and debugging time is reduced, and the resulting application programs are more structured, more readable, and more easily maintained.

Measurement subprograms in the subprogram library perform a complete measurement operation, including closing a scanner channel, taking a reading, and converting the reading to units that are meaningful to the user such as °C, microstrain, volts, and ohms. Other routines set the 3497A internal clock to the RTE system time, set the RTE system time from the 3497A clock, check the status of an HP-IB device, or set the time-out value of a logic unit. In addition, each subprogram does the error checking necessary to detect out-of-range parameters such as channel numbers and temperature values, inoperative instruments, invalid thermocouple types, and HP-IB errors. Errors cause a message to be displayed on the selected logging device, and program execution is continued. The simplicity of this approach is illustrated by the following example program.

```
      FTN4,L
      PROGRAM   EXAM1
      COMMON    ERR, BUS, SCN, DVM, LGLU
      INTEGER   ERR, BUS, SCN, DVM, LGLU, CHAN
      REAL      VOLTS, DCV, THDEG, TCDEG, TEMP1, TEMPS
C
C     * CALL INIT to initialize bus and LU assignments
      CALL INIT(0)
C     * Set the 3497A time from the RTE system time
      CALL SYTIM
C
C     *Get a dc voltage reading from channel 0
      VOLTS = DCV(0)
C
C     * Take a thermistor temperature reading
C     * from channel 1 and return °F.
      TEMP1 = THDEG(1,1HF)
C
C     * Get and display type-J thermocouple readings
C     * from channels 5 through 10 and return °C
C     * using software compensation
      DO  100 CHAN=5, 10
          TEMPS = TCDEG(CHAN, 1HJ, 1HC, 1HS)
          WRITE(LGLU, 10) CHAN, TEMPS
 10   FORMAT(/10X, "Channel: ", I2," Temp: ", F12.3)
 100  CONTINUE
```

For higher performance in temperature applications, the user may acquire a burst of measurements at higher speed, and do the voltage-to-temperature conversion later at a less critical time.

The most important utility program supplied with the 3054C system is the HLP program. With this program loaded on the RTE system, a user can recall subprogram information on-line. For example, to display information for the subprogram THDEG, simply type: RU, HLP, THDEG. This feature can even be used when working under EDIT/1000, allowing subprogram details to be recalled while constructing application programs. Also supplied is a command file which automatically compiles, loads and runs a FORTRAN application program using the 3054C library.



Lawrence E. Heyl

Larry Heyl earned a BSEE degree from Purdue University in 1974 and did high-speed logic design in the aerospace industry for five years. During this time, he received an MS degree in computer science in 1977 from the University of California at Los Angeles (UCLA). Joining HP in 1979, he developed the 3054C software. Larry is a native of Cincinnati, Ohio. He and his wife (also an engineer) live in Longmont, Colorado. Larry divides his spare time between flying, woodworking, skiing, photography, and his home computer.

Data Logging Is Easy with an HP-85/3054A Combination

by David L. Wolpert

The 3054DL (Fig. 1) includes a 3497A Data Acquisition/Control Unit with 5½-digit DVM and current source, front panel and display (optional), real-time clock, and HP-IB interface, locking drawer and optional rack cabinet, tape cartridges containing software, and system documentation. The user must also have an HP-85 computer with its integral CRT, printer, keyboard, and magnetic tape drive; and the HP-IB interface, I/O ROM, and 16K memory module options (total memory required is 30K). Some of the 3054DL functions can be performed by a 9915A Modular Desktop Computer, which is a version of the HP-85 in a rack-mountable cabinet without the keyboard, CRT and printer (see article on page 23). By selecting the proper input assemblies measurement inputs may include dc voltage, two and four-wire resistance measurements, thermocouples and resistance-temperature devices, digital bits or words (at 5, 12, or 24V logic levels), and frequency measurements or totalizing (at 5, 12, or 24V logic levels). The user may also select an actuator output assembly to do limited control functions or to drive alarm indicators following a limit test failure. The user may choose a printed record of the data, a strip chart output, display of the data on the CRT, and/or recording on magnetic tape for later analysis.

Fig. 1. *The 3054DL system combines a 3497A Data Acquisition/Control Unit with various accessories and an HP-85 as the controller in a packaged arrangement for easy and convenient data logging. The system comes with extensive software for displaying and analyzing data, thermocouple voltage-to-temperature conversions, and configuring data logging setups.*

The 3054DL system has three levels of data logging. Level 1 could be called keystroke programming of the logging function. This is the DATA LOGGER application program. To make programming DATA LOGGER simple, and because of a limited number (eight) of user-definable softkeys available on the HP-85 computer, only a limited set of logging functions is offered.

Level 2 data logging software is a set of programs that communicate with each other through common files on a tape cartridge and with the user through the keyboard and the HP-85's built-in CRT display and printer. It is based on a specialized language which is interpreted by a BASIC program in the HP-85.

Level 3 is the complete subroutine package (optional with the 3054DL) to be used in writing a complex data acquisition/control package.

To keep things as simple as possible for a user while still allowing a complex logging task, we invented a programming language directed to a data logger user. With keywords like AT, DO, START, WAIT, and REPEAT, it is readable and easy to remember and understand. For example, a typical timing setup program might consist of three lines:

- PRINT ALL; RECORD ALL—enables PRINTing (HP-85 thermal printer) and RECORDing (HP-85 magnetic tape cartridge) of data as it is taken.
- AT 8:00:00; DO DC 2,1,2,—waits for the specified time (HH:MM:SS) then sends "DC 2,1,2" to the 3497A. This will close two actuator relays (in this case, we are turning on a heater).
- START T1; WAIT 10:00; REPEAT—Next, and at ten-minute intervals, channels specified in setup T1 are measured and printed/recorded as requested.

The channel setup T1 is just as easy to understand. The data logger is set to log six channels of data as follows:

- 0:2252T/AIR TEMP - C—a thermistor(2252Ω at 25°C) is attached

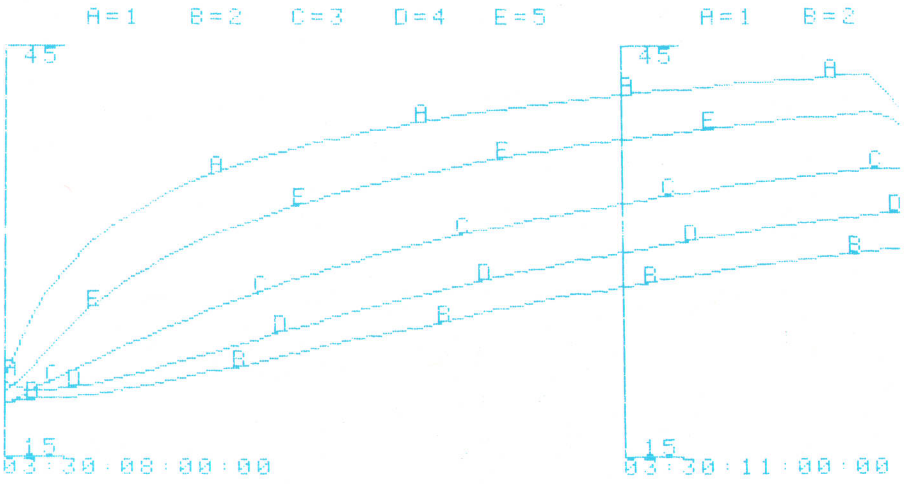


Fig. 2. *The thermal printer and graphics capability of the HP-85 make it easy to display multiple data records versus time in a strip chart form as shown at the left.*

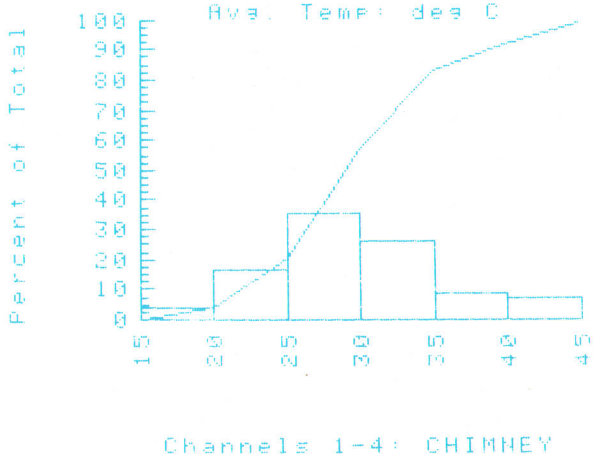


Fig. 3. *Data can be analyzed by the 3054DL system and displayed in several ways such as the histogram above.*

- to channel 0, which is labeled on the printout, and in subsequent analysis, as AIR TEMP - C.
- 1-4:T/CHIMNEY—channels 1 through 4 have type-T thermocouples attached and all are labeled CHIMNEY.
- 5:2252T;> 40; DO 2, 1, 2—another thermistor (2252Ω at 25°C) is attached to channel 5 which is labeled with the default label deg C. Channel 5 has an upper limit of 40°C. If this limit is exceeded, the string DO2, 1, 2 is output to the 3497A, which turns off the heater in this example.

This data logging setup (timing setup plus channel setup) will measure, at 10-minute intervals, the heating and cooling curve of various points in a chimney. It will heat until the temperature exceeds 40°C, then cool until the logger is stopped. The data will be printed and recorded on tape. Afterwards, the data recorded on tape will be used to plot a strip chart (Fig. 2) of the various thermocouple temperatures, or generate a temperature histogram (Fig. 3), or check the thermal tracking of two of the sensors.

A test program is included in the 3054DL Level 2 software to allow the user to verify both the user's hardware (instruments and wiring) and software (channel numbers, functions, timing, etc). Since the 3497A front panel and display need not be present in the 3054DL configuration, we have included a rudimentary front panel (displayed on the CRT of the HP-85 and addressed by its softkeys) to allow the user to set the real-time clock and take readings in a few of the basic functions.

Some data analysis capability is included with the 3054DL. With the data stored on tape cartridge the user may select from four prewritten analysis programs. The user can plot one channel versus another, channels versus time, print data, or do statistical analysis on one or all channels with a histogram of results. If this is not enough, advanced programmers can write their own analysis routines. The analysis program makes extensive use of subroutines and defined functions, and advanced users can apply these to their own problems.

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, and most recently he has been a "bit jockey", doing software development for the 3497A and the 3054DL system. He is a native of Georgia and lives in Loveland, Colorado. Dave has many outside interests, including the Colorado outdoors (skiing, whitewater rafting, hiking), and involvement with a local recording studio/advertising agency.

Acknowledgments

Special thanks to Bryan Sutula, Kevin Thompson and Barry Taylor who were the primary system software designers and whose attention to detail and dedication to keeping the schedule made the entire project a success. Paul Worrell authored the binary MERGE program needed to make automatic loading of subprograms possible with the HP-85A Computer. Doug Olsen and Ted Crawford worked together on the mechanical, thermal and industrial design of the various system packages. Wayne Goeke was responsible for the design and test procedures embodied in the verification and test connector. Dave Wolpert and Gary Ceely made a substantial contribution with their timely assistance in code translation and rigorous testing of the HP-85A and 9825B software. Larry Jones tested the complete system with such rigor that he discovered more than his fair share of bugs to be corrected before final release. John Giem in quality assurance and Bert Kolts in production engineering contributed valuable insights throughout the entire project. Neal Miller structured the system and its many options for production. Conrad Proft and Bill Hayes wrote the excellent system library manuals. Roy Barker, our R&D section manager, provided the help and encouragement that made the entire project possible.

Reference

1. L. Jones, J. Ressmeyer, and C. Clark, "Precision DVM Has Wide Dynamic Range and High Systems Speed," Hewlett-Packard Journal, April 1981.

Virgil L. Laing

Virgil Laing was born in Blue Earth, Minnesota and earned the BSEE, MSEE, and PhDEE degrees at the University of Minnesota in 1963, 1965, and 1969, respectively. He joined HP in 1968, has worked on NMOS process development and the 970A handheld DVM, and was project manager for several low-cost DMMs. Virgil is the project manager for the 3054A. He is a co-inventor on one patent related to the 970A and is a member of the Instrument Society of America. Virgil is married, has three children, and lives in Loveland, Colorado. He is a Cub Scout leader and sings tenor in his church choir. Virgil enjoys skiing, playing tennis, backpacking with his family, and duck hunting with his black Labrador retriever.

Versatile Instrument Makes High-Performance Transducer-Based Measurements

This instrument serves as the eyes, ears, and hands for a computer-controlled system that acquires data from transducers and controls equipment and processes.

by James S. Epstein and Thomas J. Heger

WHEN SPECIFYING DATA ACQUISITION instrumentation, performance can be measured by system integrity, precision, versatility, and throughput. Seldom are two applications identical. The HP Model 3497A Data Acquisition/Control Unit (Fig. 1) provides the user with a versatile HP-IB* system that has a wide range of precision measurement and control plug-in assemblies.

The versatility and some of the capability of the 3497A can be shown by looking at three of the many ways it can be used. First, the instrument may accept commands and supply data as requested one at a time by the computer in control. Second, a scan sequence consisting of a start and stop channel, voltmeter setup, time between scan sequences, and internal buffer storage for up to 100 readings may be specified. When each scan sequence is complete and the 100 readings are ready to be output, the 3497A will indicate a service request to the HP-IB. This allows optimum use of processing time in the computer since it can process previous data while the 3497A is gathering the next sequence. Third, a minimum system configuration can be established using a listen-only printer or cartridge tape unit and the 3497A in a talk-only mode. A scan sequence as described above can be set up with the data being logged on the external device rather than in the internal memory.

The 3497A has the capability of taking up to 300 readings per second in the 3½-digit mode and storing these in its internal memory. In addition, a dedicated scan-only mode was devised to provide the high-speed scanning that solid-state switches are capable of achieving. In this mode the 3497A can scan up to 5000 channels per second. Synchronization lines are provided on the back panel for interfacing to other instruments such as the HP 3437A System Voltmeter and 3456A Digital Voltmeter.

The precision of the 3497A begins with its fully guarded five-digit digital voltmeter (DVM) with a 0.003% basic accuracy specification. Analog scanning adds less than 1 μV offset error. The precision of the system is also extended to the accompanying family of digital input, digital output, counter, and analog-to-digital (A-to-D) converter plug-in assemblies (see article on page 16). All plug-ins have individual channel isolation that guarantees system measurement integrity.

A nonvolatile time-of-day clock references each measurement to real time and provides pacing and alarm clock

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*Hewlett-Packard's implementation of IEEE Standard 488 (1978).

Fig. 1. *The 3497A Data Acquisition/Control Unit is an easy-to-use system for precision measurement of transducers and thermocouples, and for control of equipment.*

capability.

Transducer-Based Measurements

In acquiring data from transducers the challenge has always been to detect low-level signals in the presence of typical laboratory and factory noise environments. For example, a type-K thermocouple has a sensitivity on the order of 40 μV/°C. Mounting this thermocouple to a transformer core induces common-mode and normal-mode noise levels on the order of volts. Thus to discern a temperature difference of 0.1 °C, it is necessary to detect a microvolt signal that is less than 0.0001% of the noise level. The 3497A and its plug-in assemblies incorporate multiple noise-reduction techniques to yield high-quality measurements in severe noise environments. These are guarding, tree switching, and signal integration periods equal to one power line cycle.

Fig. 2 shows the results obtained for various noise-reduction techniques during heat-rise testing of a transformer core. The noisy portion of the data is 50 measurements of the thermocouple output with the guard wire disconnected, the tree switch shorted and an integration time of 0.1 power line cycle. See Fig. 3 for a diagram of the thermocouple connections.

Guarding is used in system voltmeters to increase common-mode rejection (CMR). A common-mode signal V_{CM} may be caused by coupling from the ac power line, or the transducer itself may be electrically tied to the power line. If the voltmeter were ideal (having infinite impedance between the **HI** and **LO** terminals and between each terminal and the chassis) the common-mode signal would be applied equally to **HI** and **LO**, and there would be no problem. However, since the internal power supplies are referenced to **LO**, the capacitance between **LO** and the chassis (Z_{LG} + Z_{GC}) often exceeds 2000 pF. Current generated by V_{CM} then flow through the lead impedance R_X of the **LO** line, thus creating a normal-mode voltage.

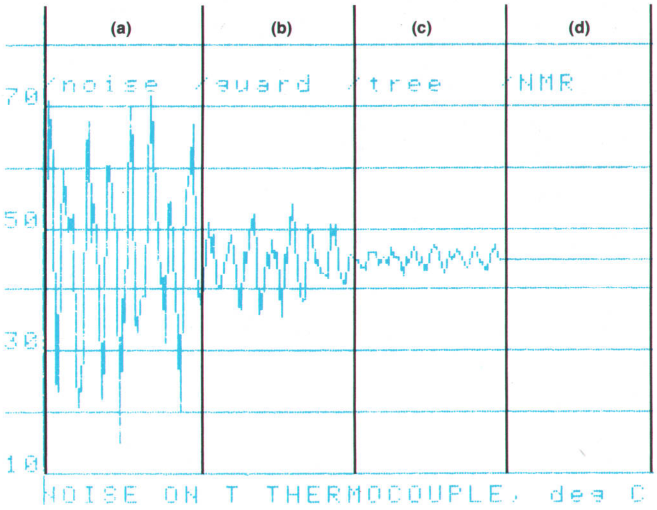

Fig. 2. *Graph of thermocouple noise for various noise reduction techniques. Each segment indicated is a sequence of 50 measurements. (a) Output with no noise reduction. (b) Noise reduced by use of guarding. (c) Noise reduced by using a tree switch with guarding. (d) Output using a tree switch, guarding, and integration to reduce noise.*

By building a metal box inside the instrument and shielding the power transformer, Z_{LG} is effectively increased since the common-mode current flows through the guard wire instead of R_X. Then the only impedance of concern is Z_{LC}, which at 60 Hz is very high (the capacitive component of Z_{LC} is about 20 pF). If $R_X = 1\ k\Omega$, guarding yields an additional 40 dB of CMR. The guarded portion of the results in Fig. 2 shows the improvement during another 50 thermocouple measurements.

The number of analog points in a system can also affect the accuracy of the measurement. By using a tree switch as shown in Fig. 3 for each group of 20 channels in the analog multiplexer plug-ins the interchannel capacitance in a large system is reduced significantly. This capacitance (C1, C2, C3), which comes from open switches and printed circuit board traces, can be responsible for feedthrough and settling problems. Consider that each switch in a typical n:1 channel scanner contributes another parallel C1, C2, and C3. With the tree switch, groups of 20 parallel channel capacitances are in series with a single tree switch capacitance, effectively reducing the capacitance of each block of 20 switches to that of a single switch.

Integration inherently provides noise rejection since the A-to-D converter's output is the average of the input voltage during the sample period. By setting the sample period equal to one power line cycle, line-related noise and its harmonics are virtually eliminated. Normal-mode rejection (NMR) is greater than 60 dB at 60 Hz.

Using the A-to-D conversion method used in the 3456A DVM[1] allows 50 readings per second with >60 dB NMR. Thus, without going through time-consuming digital filtering, the first answer returned to the user is accurate and the effective ac CMR at the line frequency is >150 dB. The results of using a tree switch and integration over one line cycle are also shown in Fig. 2.

Analog scanning flexibility is enhanced further in the 3497A Data Acquisition/Control Unit by allowing each block of ten channels (called a decade — hence a block of 100 channels is called a century) to be disconnected separately from the common bus. This allows the formation of multiple 10:1 scanners for measurement and stimulus switching. Because more than one switch can be closed simultaneously, four-wire resistance and single-ended measurements can be done. For maximum economy single-ended measurements with 60 channels per plug-in (as opposed to 20 three-wire measurements) can be done when signal levels are high (millivolts as compared to microvolts). Also, locations for single-pole filtering of each input channel or a current shunt are provided on the multiplexer plug-in assemblies.

Additional capability to condition transducer measurements before the A-to-D conversion is often needed. An isothermal block whose temperature is known to 0.1°C is necessary to handle thermocouples. A precision current source is required for RTD (resistance-temperature detector), thermistor, and other resistance measurements. Frequency counting is needed for flow measurement and the determination of digital on/off states is essential. Strain gauges require a bridge-completion network, and control, both proportional and on/off, is needed to provide stimulus and to complete measurement feedback loops.

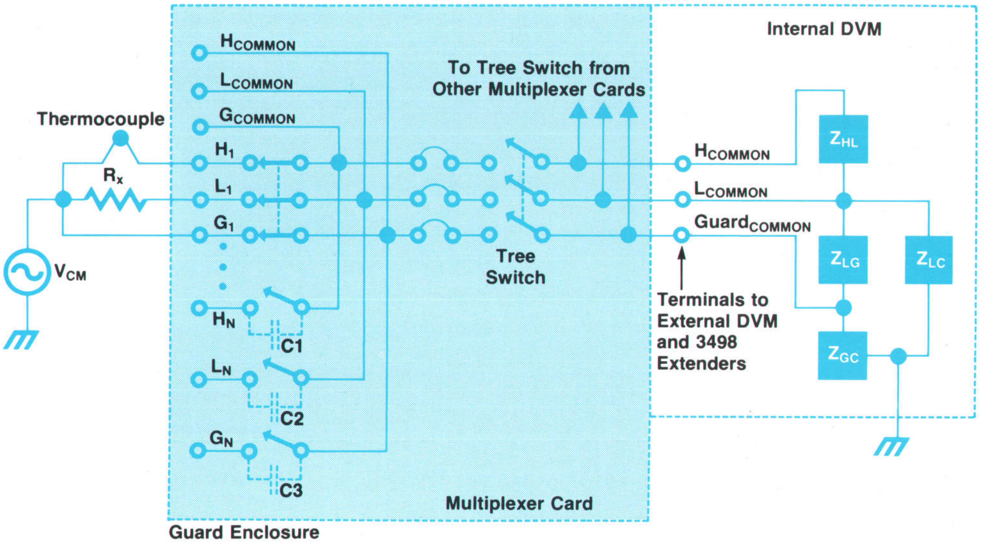

Fig. 3. *Thermocouple connections to a 44421A 20-channel multiplexer plug-in assembly in the 3497A showing the internal circuits for the tree switch and the guard.*

Because of this assortment of requirements, a system must be able to be tailored to a customer's application. The 3497A Data Acquisition/Control Unit and its optional plug-in assemblies provide user flexibility in all of the above areas while maintaining performance accuracy and isolation for data integrity. Fig. 4 shows a block diagram of the 3497A system and Table I outlines two possible 3497A system applications using the plug-in assemblies.

Voltmeter Module

The voltmeter module and the multiplexer plug-ins form the heart of the 3497A Data Acquisition/Control Unit. The voltmeter module was developed in parallel with the HP 3456A DVM.[1] Using Multi-Slope II integration as the analog-to-digital (A-to-D) conversion technique, the 3497A can provide sensitivities from 1 microvolt to 120V with four ranges and 120,000 counts of resolution.

Much of the flexibility of this module comes from the integrating A-to-D converter. Integration was chosen to provide normal-mode rejection at power line frequencies for signal integrity. Traditional dual-slope converters have a theoretical maximum sample rate of 30/s, which may be too low for some applications. By digitizing the most significant digits of the input signal during the conventional runup period and providing multiple rundown rates, the 3497A DVM module produces 50 readings/s with good normal-mode rejection.

Decreasing the length of runup allows improved reading rates but with the loss of normal-mode rejection and resolution. To satisfy as many measurement problems as possible, the voltmeter module offers a user-programmable speed/resolution tradeoff. Sample rates of 300 readings/s with 3½ digits of resolution, 200 readings/s with 4½ digits of resolution and 50 readings/s with 5½ digits of resolution are fully programmable functions for this module.

A digital zeroing technique is used on the input to the A-to-D converter to compensate for temperature drift, since it is difficult to find FETs (field-effect transistors) whose inputs are matched to better than 5 $\mu V/^\circ C$. The input signal can be disconnected and the input shorted to **LO**. With this configuration a conversion is made and the internal offset error voltage is stored in the inguard controller. Then the

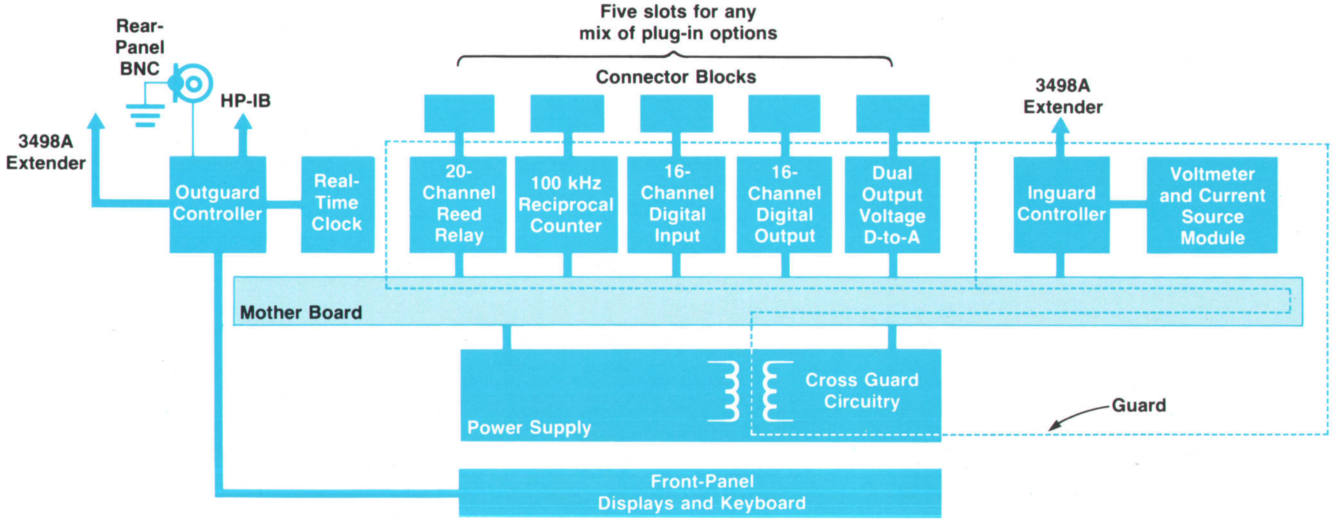

Fig. 4. *Block diagram of the 3497A Data Acquisition/Control Unit.*

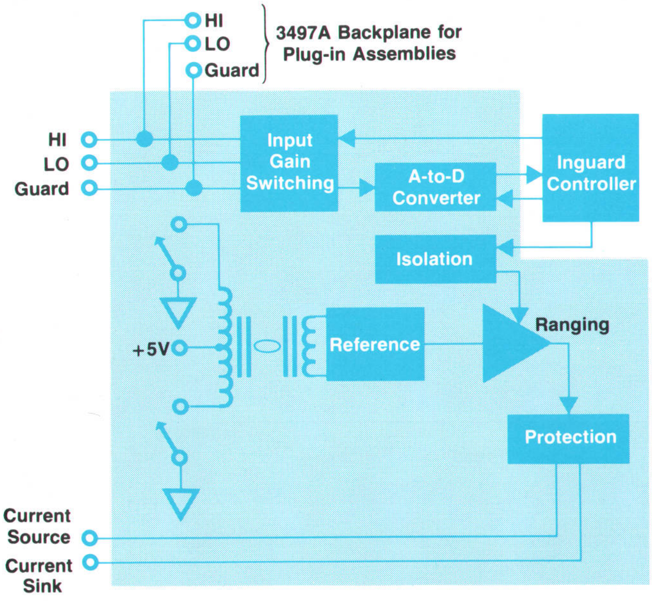

Fig. 5. *Block diagram of 3497A voltmeter module.*

normal measurement is made and the controller starts its counting process with this offset. Digital zeroing is a programmable function. With Voltmeter Zero on, the input signal plus internal offsets are digitized. A second measurement is then made of the offset voltage. With Voltmeter Zero off, the last offset measured on a specific range is stored and used for future input measurements.

A highly stable fully floating current source in the voltmeter assembly (Fig. 5) provides excitation for RTDs, thermistors and other resistance measurements. User-programmable output levels of 10 μA, 100 μA, and 1 mA combined with the DVM provide resistance measurements from 1 mΩ to 1 MΩ. An important consideration when making highly accurate resistance measurements is how the four-wire technique is performed. The current source is derived by chopping the +5V **LO**-referenced power supply at 25 kHz. This signal is put through two pulse transformers that are coupled by a single turn. The single turn reduces the feedthrough capacitance to 1 pF and thus minimizes injected current. The current source is completed by using a stable voltage reference and some custom fineline resistors.

In previous system voltmeters, the maximum lead impedance that the ohms converter could accept was limited to one-tenth of the full-scale level. Thus 20Ω of lead impedance causes problems when measuring 120Ω RTDs. This is because the amount of excitation voltage drop across this lead impedance causes internal ranging problems. With a scanned system the problems increase since lead impedances caused by long runs or solid-state channel multiplexing will usually exceed this level. Because the 3497A current source output has 15V of compliance and truly floats, lead impedances up to 150 kΩ can be tolerated.

The firmware supporting the voltmeter module provides some specific advantages for the system user. Up to 100 readings can be stored in internal memory for future recall. A scan sequence can be executed without HP-IB controller intervention. Thus the controlling computer is able to do other tasks, and the 3497A notifies it when the buffer is full.

Because analog inputs may have different settling time requirements, a programmable wait is provided. After a channel is closed and before the measurement is executed, a user-specified delay can be inserted.

Calibration of system components often requires removal of the product from a rack. This is eliminated by providing complete calibration of all voltmeter and current source ranges behind a hinged front panel. There are eight adjustments for the complete calibration: five for dc volts and three for the current source.

Front-Panel Control

With the 3497A front panel, the user can do the setup, debugging, and troubleshooting of the system without any software development. Also, because all commands can be executed from the front-panel keyboard using the same syntax as used over the interface bus, the program string can be tested manually. The internal display effectively parallels the HP-IB I/O.

Table I
Two Application Examples for 3497A Based System

3497A and Plug-in Assemblies *	Measurement Function	Engine Design Analysis	Facility Monitoring
DVM, 44422A	Temperature: Thermocouples	Coolant and Oil Temperature	Heating and Air Conditioning
DVM, 44421A	RTDs	Hot Spot Analysis	Fire Detection
DVM, 44421A	Thermistors	Exhaust Temperature	Motor Overloads
DVM, 44421A	IC Sensors	Cooling System Analysis	Power/Facilities Use
DVM, 44421A	dc Voltage	Battery Voltage	Backup Lighting
DVM, 44421A	Resistance	Continuity or Isolation	Continuity, Isolation, Lighting Level
44426A	Frequency, Period, Pulse Width, Totalize	Fuel/Air Flow, r/min, Event Counter	Air/Water Flow, Power Use, Traffic Monitoring
44425A	Digital Input	Status Lines, Limit Switches	Status Lines, Security Checks
44425A	Digital Interrupt	Interrupts	Alarm Conditions
44428A	Digital Output	On/Off Valve Control	On/Off Valve and Vent Control, Data Display
44428A	Actuator Output	Engine Load Control	Pumps, Exhaust Fans, Alarms
44429A	0 to ±10V Programmable Voltage	Proportional Throttle Control	Lighting Control
44430A	4-20 mA Programmable Current	Current Control Loop	Heating/Cooling Control
44421A	High-Speed Digitization and Scanning	Continuous Real-Time Monitoring	Continuous Real-Time Monitoring
Real-Time Clock	Time	Data Logging	Logging Events, Data

*See article on page 16 for descriptions of plug-in assemblies. Real-time clock is internal part of 3497A. DVM can be external unit or voltmeter module in 3497A.

Internal Control of the 3497A Data Acquisition/Control Unit

The operating system for a data acquisition and control unit with a large number of plug-in options must be flexible enough to handle a wide variety of functions and remain straightforward and easy to use. The 3497A instruction set is a consistent set of commands that can be easily expanded to handle additional plug-in assemblies and is compatible with the various computers that can be used to control the 3497A. In addition, links to an option ROM (read-only memory), which can be added at a later date, provide a high degree of freedom for expansion.

The typical command consists of two alpha characters followed by a numeric field. The alpha characters indicate the command type (e.g., AC is analog close), and the numeric field indicates the parameters for that command. There are six groups of commands which can be identified by the first alpha character in the command. The groups pertain to functional parts of the 3497A as follows: system, analog, timer, voltmeter, digital and option. The option commands are discussed later. Each character is accepted into the instrument via the HP-IB or keyboard and interpreted as it is received. If the command characters are not valid, the command sequence is aborted and the operator is signaled by a front-panel beeper and an SRQ (service request) signal on the HP-IB. When the entire command is received, it is stored in an execution buffer to be acted upon. If another command is received, it will also be processed until it is completed. No further command characters will then be accepted until the first command execution is complete.

In an acquisition and control unit, it is important that commands are executed sequentially, that is, a command is not executed until all previous commands have been completed. An example will illustrate this point. Suppose that the command sequence is VC1VT3 (set voltmeter current source on 10-μA range, trigger voltmeter). Here the current source must be completely turned on and settled before the voltmeter reading is initiated. The proper settling time is built into the 3497A to give optimum performance.

To make programs more readable, all lowercase alpha characters are ignored. Therefore, a program line may contain the command Analog Step or simply the command AS to advance the channel. Spaces, line feed and colons are also ignored. Each command is terminated by a carriage return or by any uppercase alpha character.

The keyboard is primarily used as an aid in setup or a manual backup mode, and in a talk-only mode in a minimum system configuration. For aid in setup, certain commands should be easy to send such as AS (analog step) or TD (time of day). For backup, software debugging, or talk-only mode, all capability should be available. The keyboard has two separate modes to serve these purposes. One is a key-per-function mode where one keystroke will step a channel or read the time of day. Then, to enable the full command set, a shift key is used which allows the commands to be sent in the same double-alpha-plus-numeric form as would be sent via the HP-IB.

A highly flexible output format further enhances the 3497A's application range. The voltmeter has three different output formats. Standard ASCII format terminated by carriage return and line feed is ideal for free-field inputs into a computer. Packed format reduces the number of bytes sent over the HP-IB interface from 13 to 3 bytes to enhance the throughput. Finally a data-logger format provides ASCII output of the measured channel, the measured voltage and the time of day.

The operating system firmware is organized as two separate internal entities: the interrupt controller and the system controller. The block diagram in Fig. 1 illustrates the general firmware organization.

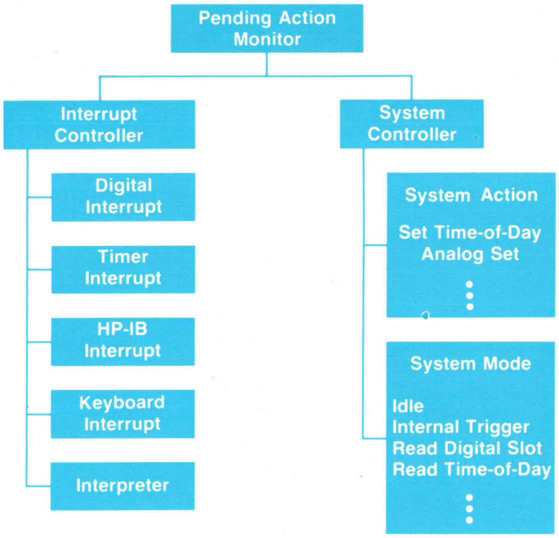

Fig. 1. *Firmware organization of the 3497A Data Acquisition/Control Unit.*

The interrupt controller handles all I/O requests and processes them for the system controller, which performs all of the designated actions. The pending-action monitor passes data between the two entities. For example, when a character is received via the keyboard or HP-IB, the system controller is interrupted and the interrupt controller takes over to examine the character. If it is valid, the interrupt controller will interpret it and store it in an interrupt buffer. If the instruction is complete, the interrupt controller will store the action to be executed and any associated data in a buffer and set a flag for the pending-action monitor. Control is then returned to the system controller. When the system controller completes the present action, it will call the pending-action monitor to see if any more actions are to be taken. If so, it will get the new instruction and data and proceed to execute them. After all actions are completed, the system controller looks at the present mode of the instrument (e.g., voltmeter internal trigger, read time-of-day, idle, et cetera) and performs the required sequence. The interrupt controller also handles timer and digital interrupts by sending the SRQ signal to the HP-IB.

Two additional features are the option ROM links and system read/write. These features are provided to allow for easy expansion of the 3497A by adding new plug-in assemblies and associated new instructions. The option ROM link consists of a check by the interpreter to see if an option ROM is present; if so, it will then call the option ROM interpreter to try to interpret the command. If the command is an option command, the option interpreter will set up the correct system action, data buffer and pending-action flag just as the main interpreter would. Therefore, new commands can be added as necessary. The counter is the first plug-in option to use the option ROM. In addition, the systems's read and write commands are provided in any slot. Typical use of the system read command is an interrogation of each slot to identify what plug-in is present. A system program can then be written to interrogate the slots in a larger system composed of many extenders and display the configuration of the entire system.

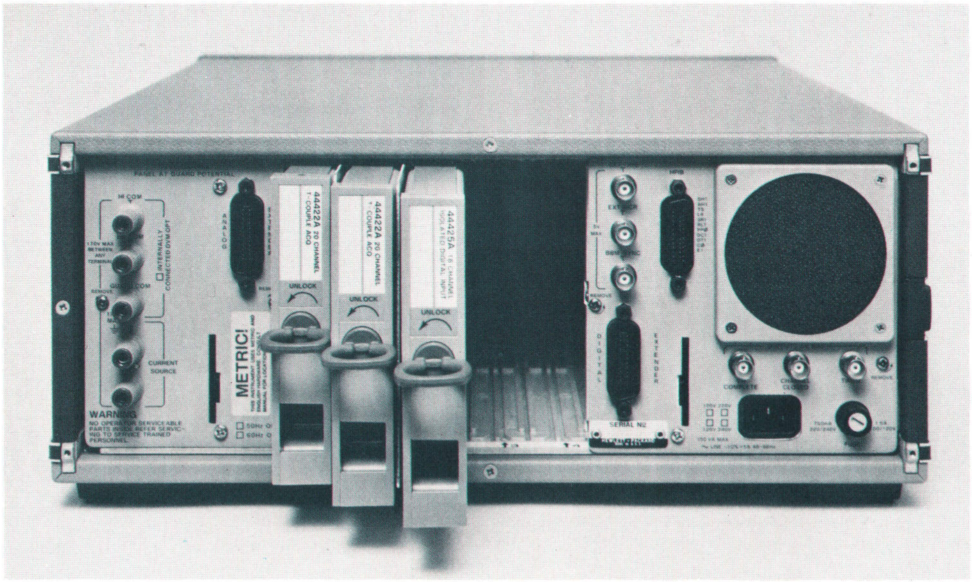

Fig. 6. *The 3497A has five slots in the rear where the user can easily insert any combination of the available plug-ins to configure the system for a particular application.*

Card Control

Each of the five 3497A plug-in slots (Fig. 6) can take any of the acquisition or control assemblies available. Control for the multiplexer plug-in comes from the inguard controller whose logic is referenced to the **LO** terminal of the A-to-D converter. This minimizes the signal-to-earth capacitance, thus increasing common-mode rejection. The inguard controller talks to the plug-in assemblies by decoding the century and decade of each slot and presenting two lines of decade information and four unit lines to each plug-in. The multiplexer assembly then performs a break-before-make handshake with the controller to complete the switching process. An additional latch line allows up to four channnels to be closed simultaneously to facilitate four-wire resistance and single-ended measurements and the simultaneous multiplexing often required for an input to be switched to another measurement unit.

The 6800 outguard controller controls all of the other plug-ins in the 3497A. By extending the microprocessor's address and data bus to the plug-in assemblies, the controller exchanges information with the plug-ins as if they were eight bytes of RAM (random-access memory). The first byte on each plug-in indicates its type (analog output, digital input, et cetera) and status (ready/busy). Writing to the seven remaining bytes defines the actions to be performed by a plug-in assembly. Reading these seven bytes returns the results of these actions. To eliminate the need for polling, the processor interrupt line is available to any I/O assembly along the backplane of the 3497A.

Nonvolatile Real-Time Clock

The outguard controller has a dedicated interface for the real-time clock (RTC). Because the clock has to be nonvolatile, the standard microprocessor-controlled clock designs that require power distribution greater than one watt are not feasible. To provide a highly versatile clock with time-of-day, elapsed-time, time-match, and time-interval capability a low-power, single-chip microprocessor (8048 or 8021) was chosen. The design is outlined in Fig. 7.

When a write operation takes place, the 6800 outguard controller writes the data word into U3. It then sets the outputs of U5 and U2 for the RTC processor. When the RTC processor sees U2 high, it checks U5 to determine if a write (U5 set) or a read (U5 clear) is in process. During a write cycle, the RTC processor enables the outputs of U3 to drive its data bus and reads this data. It then clears U2 to indicate that the data transfer is complete. A similar event takes place to read from the RTC. The RTC processor, after detecting that U2 is set and that U5 is clear, latches data into U4 and clears U2 to indicate that valid data is in U4. This data is then read by the 6800 microprocessor.

Since only the RTC processor has battery backup, the interface circuitry between the two processors is ignored by

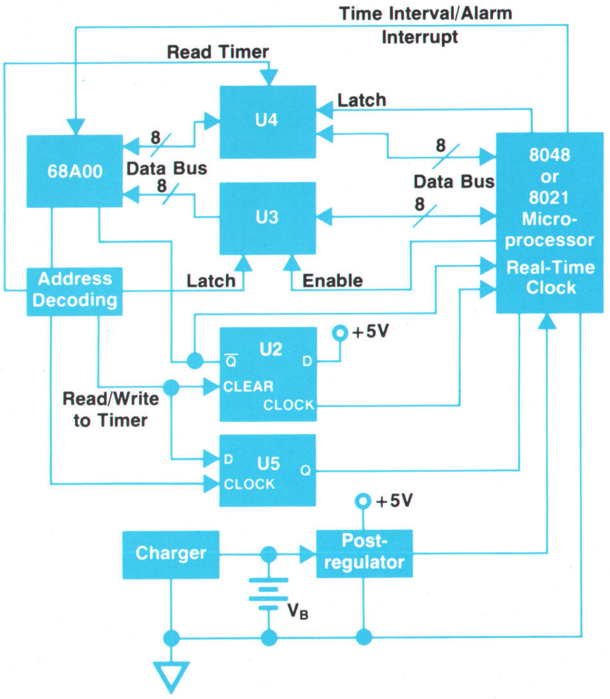

Fig. 7. *Block diagram of the real-time clock in the 3497A.*

the RTC when the main power to the 3497A is removed. This insures reliable communications and prevents any hangup modes in the event of power loss while exchanging data with the 6800 system processor.

The RTC printed circuit board can accept either an 8048 or 8021 microprocessor. These processors have internal timers which are programmed to overflow at a rate of 10 Hz. Firmware then updates the time of day and the elapsed time and checks for a Time Alarm or Time Internal match. Day and month calculations are also done in firmware. The pacing outputs are generated with a programmable divide-by-n circuit in hardware to handle rates up to 10 kHz.

Mechanical Design

Ease of connection, reliability, and serviceability were mechanical design goals for the 3497A. Any of the mainframe boards can be accessed by the removal of no more than four screws because both the front and rear panels give access to the entire instrument. Opening the hinged front panel allows voltmeter adjustments and the power line setting to be made. Accessibility to the front-panel and power supply boards is obtained also from the front. The main controller with the RTC and the inguard controller with the voltmeter can be pulled out from the rear by removing two screws.

The real key to user accessibility is in the plug-in option area. The acquisition and/or control plug-in assembly options are easily inserted in any of the five slots available in the rear panel (Fig. 7). If additional slots are required, the 3498A Extender can be used to expand the system.

The extender has ten plug-in slots and is joined to the 3497A Data Acquisition/Control Unit by two 24-pin connectors. One is used to provide outguard control via extended address and data bus signals from the 3497A mainframe controller. These signals are buffered and decoded in the 3498A to provide the same control lines that are on the 3497A backplane. The other cable (a second cable is required to preserve isolation between **LO** and earth) presents century, decade and unit lines, which are decoded and provided to the backplane of the extender.

A 3498A provides an additional 200 channels if a multiplexer plug-in is installed in each slot. Up to 1000 analog multiplexing channels and 1380 digital channels can be supported in the 3497A system by adding 3498As.

Acknowledgments

Besides the authors, the electrical design team for the 3497A and its plug-in assemblies included Eric Wicklund, Ron Firooz, Dave Leonard, Pat Redding, Duff McRoberts, Rick Hester, and Virgil Leenerts. Eric did the voltmeter option, Ron did the main controller and digital-input option, Dave did the inguard controller, reed-relay acquisition card and the digital-output option, and Rick did the D-to-A option. Pat designed the counter and Virgil designed the power supplies.

Bob Moomaw and Mike Williams worked on the mechanical design and the 3498A Extender was done by Greg Hill and Greg Arneson. Jon Pennington did the industrial design. Virgil Laing was the original project manager for the 3497A and provided invaluable definitional work and marketing data.

The authors are indebted to Roy Barker, our section manager, who provided the perspective and guidance to implement this project, and to Bill Bush in product marketing for his many helpful ideas.

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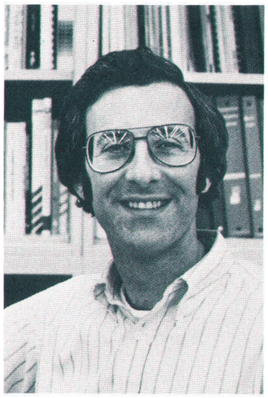
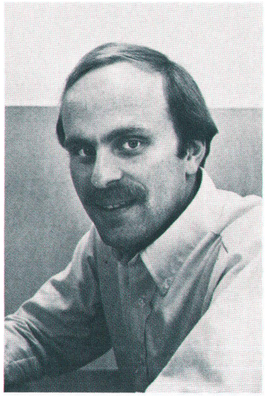


James S. Epstein

Jim Epstein joined HP in 1972 with previous work experience as a design engineer. He worked on the design of the 3820 Total Station and now is an R&D project manager for sources and analyzers. Jim was born in New York City and attended the Polytechnic Institute of New York, earning the BSEE degree in 1964. He served in the U.S. Army from 1965 to 1967 and then studied for the MSEE degree at the University of Missouri at Rolla, receiving it in 1969. Jim is co-inventor on a patent for a surveying instrument and method and is a member of the Instrument Society of America. He is married, has three sons, and lives in Loveland, Colorado. Jim is on the parent-teacher council at a local elementary school and during his leisure time enjoys playing tennis, swimming, and skiing.



Thomas J. Heger

Tom Heger has been with HP since 1973. He has a BSEE degree awarded in 1972 by the University of Wisconsin at Madison. While working at HP, he completed the requirements for the MSEE degree at Colorado State University in 1976. Tom worked on calculator I/O at HP's Corvallis Division and the 3455A DVM at the Loveland Instrument Division. He was the R&D project manager for the 3497A. He is a member of the Instrument Society of America and a native of Milwaukee, Wisconsin. Tom is married, has one son, and lives in Loveland, Colorado. He enjoys playing tennis, bicycling, and backpacking.

Plug-in Assemblies for a Variety of Data Acquisition/Control Applications

by Thomas J. Heger, Patricia A. Redding, and Richard L. Hester

DATA ACQUISITION/CONTROL applications require various measurement and actuator capabilities such as channel multiplexing, digital input and output, counting, and thermocouple compensation. For example, to monitor and control a solar heating installation, temperatures, air and water flows, and solar radiation intensity need to be measured and/or controlled.

To do these and other similar tasks, a variety of plug-in assemblies (Fig. 1) is available for the HP Model 3497A Data Acquisition/Control Unit described in the article on page 9. Some of these plug-ins are:

- Option 010 44421A 20-Channel Guarded Acquisition. This plug-in assembly is used to switch signals to other assemblies, instruments, or the digital voltmeter module in the 3497A.
- Option 020 44422A 20-Channel Thermocouple Acquisition. This unit uses the same relay multiplexing as Option 010 above, but adds a special isothermal connector block for thermocouple compensation.
- Option 050 44425A 16-Channel Isolated Digital Input. Sixteen lines of digital data such as switch closures and various logic levels can be sensed by this plug-in. Eight of the lines provide interrupt capability.

Fig. 1. *The 3497A Data Acquisition/Control Unit has a variety of plug-in assemblies that measure physical parameters, actuate devices, input and output digital data, convert digital commands to voltages and currents, and scan many channels.*

- Option 110 44428A 16-Channel Actuator Output. Power levels up to 100V and 1A can be switched by each channel to actuate external devices and test fixtures.
- Option 060 44426A 100-kHz Reciprocal Counter. This assembly can count events (up or down from a programmable start point), and measure pulse widths and periods.
- Option 120 44429A Dual-Output 0-±10V D-to-A Converter. This assembly provides two independently programmable voltage sources for test excitation or to control voltage-programmed devices.
- Option 130 44430A Dual-Output 0-20 mA or 4-20 mA D-to-A Converter. Similar to Option 120, this unit provides two independently programmable current sources. Each source can be set to operate in either the 0-to-20-mA or 4-to-20-mA range. This assembly can be used for proportional control loop applications such as closing valves.
- Option 070 44427A (120Ω) and Option 071 44427B (350Ω) 10-Channel Strain Gauge/Bridge Assemblies. These plug-ins provide bridge completion for strain gauges and other transducers such as pressure sensors and load cells. An internal half-bridge shared with each channel allows measurement of up to ten bridges per assembly.

All terminal connections to the 44421A, 44422A, 44425A, 44427A/B and 44428A plug-in assemblies are made using individually removable terminal blocks. This makes it easy to move a data acquisition/control system from one location to another because the external sensors and actuator devices can be left in place and reconnected quickly at another time.

Analog Multiplexers

The 44421A and 44422A analog multiplexers consist of 20 dry reed relays, each switching **HI**, **LO**, and **GUARD**. These plug-ins are used to switch individual input signals into the 3497A's voltmeter module or to other assemblies or instruments. Channels are organized into two decades (10-channel blocks) on each plug-in assembly. One channel at a time in each decade can be closed, allowing two channels in each plug-in to be closed at the same time. These reed relay assemblies allow scan rates of 300 channels/second with thermal offsets of less than 1 μV for accurate measuring of low-level analog signals from transducers. All relays are break-before-make configuration and provide 170V common mode isolation.

To preserve signal integrity the multiplexer plug-ins employ full guarding and tree switching. Guarding, as discussed in the preceding article, provides a means for measurement devices to increase their **LO**-to-earth impedance.

Guarding also increases the effective impedance on printed circuit boards in the 3497A. As an example, the coil

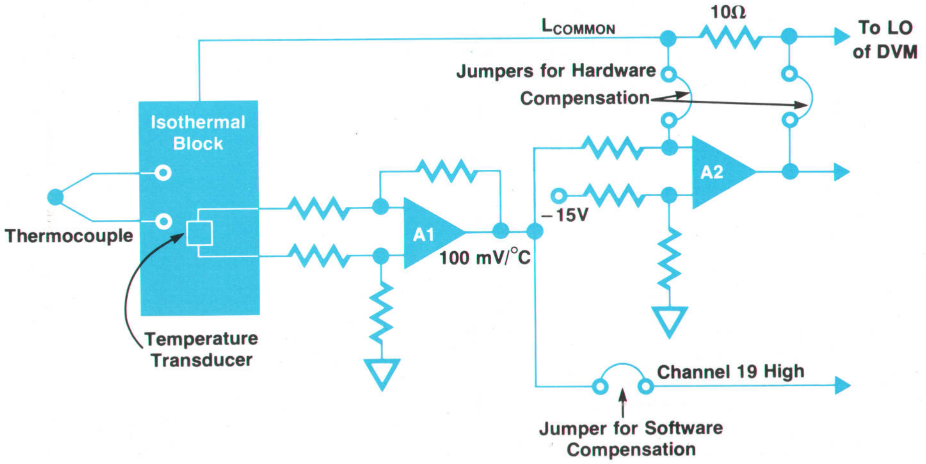


Fig. 2. *Thermocouple compensation circuit. Using the indicated jumpers, the circuit can be wired to do either hardware or software compensation.*

drive for the relays comes from a power supply referenced to **LO**. This can cause a leakage current to flow from the coil through the guard wire and back through any source impedance in the **LO** wire. To minimize this effect, which is a concern at high humidity levels, a printed-circuit-board trace tied to the power supply's low line is run parallel to the coil drive lines, thus providing a return path outside the measurement loop.

Multiple design techniques were used to minimize thermally generated EMF in the multiplexer plug-in assemblies. The largest source of this error voltage occurs within the relays because of a thermoelectric effect caused by the dissimilar metals of the reeds and copper leads. Heat generated by the power dissipated in the relay's coil can cause a temperature gradient along the relay leads, thus creating thermoelectric voltages. The multiplexer plug-in incorporates circuitry that applies full power to the relays for fast closing and then reduces the drive to a hold level, thus reducing the coil power and coil-generated thermal gradients. This also allows the relays to open faster, because there is less energy stored in the coil.

A shield referenced to **GUARD** is tied onto the back side of the relay multiplexer plug-in to reduce external thermal gradients. An adjacent D-to-A plug-in, because it has high power dissipation, may set up local gradients that add to the thermally generated EMF of an analog channel. An aluminum shield balances this out and prevents convective air flows around the relays.

Finally the relays are made with a beryllium-oxide plug at the interface between the relay leads and the copper legs coming out of the bodies. This plug is an excellent electrical insulator (>1000 GΩ) and a thermal conductor which eliminates any temperature difference between the **HI** and **LO** switches. Thus any EMF generated in the **HI** switch is matched by an identical EMF generated in the **LO** switch and so is turned into a common-mode voltage which is rejected by the 3497A DVM.

The multiplexer plug-ins work with any one of three terminal block assemblies. A voltage input block provides screw terminals for voltage measurement and has space for filtering on a per-channel basis as well as resistive terminations for current measurements. Another assembly provides bridge-completion networks for strain gauges, while the third terminal assembly provides an isothermal block for thermocouple connections.

Thermocouple Compensation

Widely accepted and easy to mount, thermocouples are probably the most common temperature transducers. Besides requiring microvolt-level measurements, thermocouples require compensation to correct for the fact that the voltage measured by the DVM is a combination of the desired thermocouple voltage and two additional thermoelectric error voltages that are generated where each thermocouple wire is connected to the measuring instrument.

The 3497A system incorporates both software and hardware compensation for seven thermocouple types. An electronic ice point is used. An isothermal terminal block is provided for the 44422A multiplexer plug-in so that the temperature of several terminals can be sensed with only one sensor. This block is made by building a four-layer printed circuit board with thick outer layers of copper. The terminals and a temperature sensor are soldered within a matrix of solder-filled plated-through holes in the printed circuit board. This design provides a thermal short (<0.2°C temperature gradient) between the 20 inputs and the temperature sensor. The sensor's output is preconditioned to produce 100 mV/°C.

The user may select either hardware or software compensation. Hardware compensation (Fig. 2) consists of further conditioning the sensor's output to a particular thermocouple type and inserting a voltage across the 10Ω resistor to cancel the unwanted thermoelectric effects. In software compensation the 10Ω resistor is shorted and the current source driving it is disconnected. The user must then measure the sensor output (internally jumped to channel 19) and calculate the thermoelectric effects for the thermocouples at both the H and L inputs to the isothermal terminal block. By subtracting these effects in system software (thermocouple routines are available in the 3054 systems, see page 4) the user can determine the correct temperature at point T.

Hardware compensation has the advantage of being faster but is restricted to only one type of thermocouple per terminal block. Software compensation requires more computer manipulation and a separate channel to measure the temperature sensor on the isothermal terminal block. However,

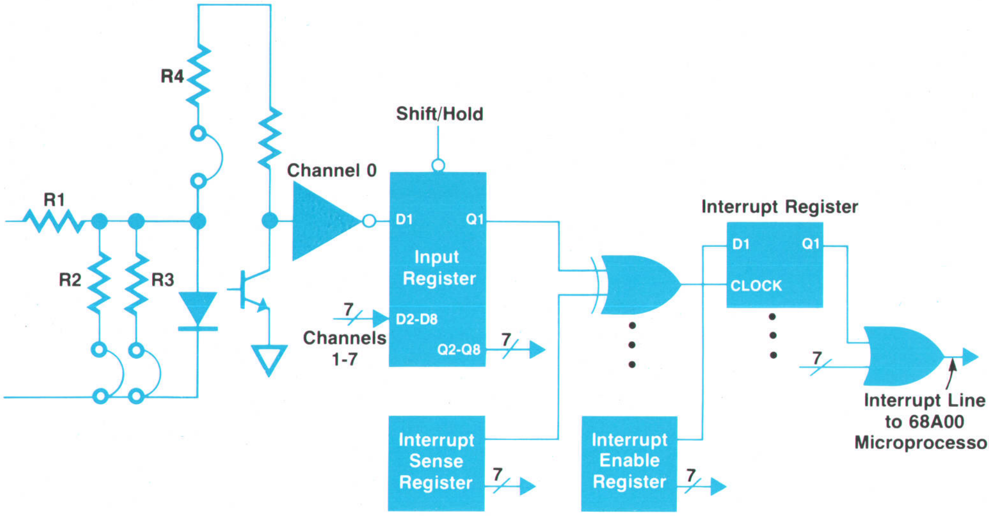


Fig. 3. *Simplified schematic of one of the 16 channels in the 44425A digital input plug-in assembly.*

the software approach can be used for any thermocouple type and the terminal block also can be used for other voltage inputs.

Digital Input and Output

The isolated 44425A digital input (Fig. 3) and 44428A digital output actuator plug-ins can sense external on/off or high/low events and produce contact closures, alarm outputs, and solenoid on/off control. Optical isolators provide channel isolation for the digital input word, which allows the user to see the state of 16 input lines simultaneously. Signal conditioning of each line is simply done by using appropriate jumpers on the plug-in to allow +5V, +12V, and +24V logic levels as well as contact closures to be used as inputs. The digital input plug-in allows the user to interrupt the 3497A by activating the service request line (SRQ) over the HP-IB. Channels 0 through 7 have individual enable and sense bits that can be programmed to specify which channel(s) and which sense (high-to-low or low-to-high transition) will cause an interrupt.

The digital output plug-in assembly consists of sixteen form-C-relay isolated channels. Mercury-wetted relays are used because they are bounceless and can be used to interface to logic circuits when speed is not a concern. The contacts, which have a lifetime of 10^{10} operations and the capability of switching signals up to 100V at 1A, find applications in actuating solenoids, sounding alarms, and secondary switching of ac power controls. For matrix-switch applications each actuator plug-in can be used to form a 4×4 matrix (or a 4×4 section of a larger matrix) to provide additional flexibility not found in an n:1 switch.

Both the digital input and digital output plug-ins provide a two-wire gate/flag handshake so that they can be used to interface to external logic. The gate/flag handshake synchronizes the data exchange by allowing the output device to indicate when data is valid and the input device to indicate when data is accepted.

Counter

The 100-kHz reciprocal counter plug-in assembly for the 3497A system adds the capability of measuring low-frequency signals with a variety of convenient features. Many data acquisition and control applications require the measurement of time or number, or the generation of pulses. Examples include measuring flow, counting events, and positioning of devices. The instrument that handles these applications should integrate easily into the system, not require continuous controller attention, and have a reasonable cost.

Some features of the counter plug-in are counting up and down from programmable start points in the range of 0 to 999,999, and performing period and pulse width measurements. It has the ability to count up or count down on selectable rising or falling input signal edges, to perform period measurements from rising to rising or falling to falling edge, and to perform pulse width measurements from rising to falling or falling to rising edge of the input signal. In addition, the counter can interrupt the 3497A controller because of a measurement complete or overflow condition. Edge trigger selection and interrupt enabling are completely programmable. The counter assembly also features "reading-on-the-fly" without disturbance of incoming counts, as well as a separate syntax for triggering and reading of a measurement. The latter feature allows other system tasks to be accomplished during a counter measurement. An output line provides a hardware nonmaskable interrupt signal.

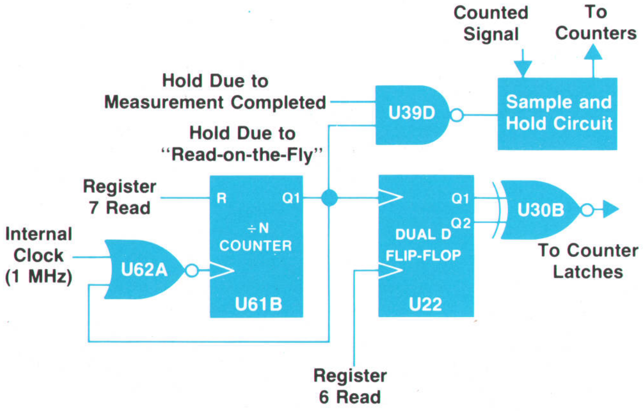


Fig. 4. *"Read-on-the-fly" circuit of the 44426A counter plug-in assembly makes it possible to read data while continuing the counter measurement.*

The period and pulse width measurements use the reciprocal frequency measurement technique. The input signal provides the gate and the counter's internal clock is counted for the duration of the gate signal. When measuring low-frequency signals, this is the preferred method, because more counts per measurement are obtained.

The frequency of the internal clock is divided down from a 5-MHz crystal-controlled oscillator to 100 kHz or 1 kHz, depending on the range selected. The start and stop signals are synchronized with the internal clock so that a maximum of one count (one period of the internal clock) of error occurs at this point. On period and pulse width measurements, 1, 100, or 1000 inputs can be averaged depending on the function selected. The answer is computed in software. The difference between the period and pulse width circuitry is that the pulse width start and stop signals are generated for the duration of the input pulse and not for the full period. When averaging over 100 or 1000 pulses, the gate must be on during the pulses being measured, and off during the other part of the cycle, rather than remaining on continuously for 100 or 1000 cycles as is done for period measurements.

The read-on-the-fly feature of the counter card refers to the ability of the counter string to be read at any time without interfering with the counting process, whether it be during a count up, count down, period, or pulse width function. The read-on-the-fly capability is most useful when counting up or counting down because it ensures that a read operation will always return valid answers and not miss or skip incoming events. It can also be helpful during period or pulse width measurements, especially if low-frequency inputs are being measured. The counter can be interrogated at any time to see how the measurement is progressing by executing a counter read-without-wait command. This is useful because the measurement time is determined by the input signal, which has an unknown duration, and not by an internal measurement cycle. Also, this permits other system actions during the period or pulse width measurement.

A diagram of the read-on-the-fly circuitry is shown in Fig. 4. The signal to be counted is sent to the sample-and-hold circuit controlled by U39D. If U39D's output is low, the signal flows directly to the counters. If it is high, the circuit holds the signal at its current level.

When a counter read-without-wait command is executed, the 3497A controller sends a register 7 read strobe to the reset line of U61B. This causes Q1 of U61B to go from high to low, thereby holding the present level of the input to the counter string. On the second rising edge presented to the clock of U61B, Q1 returns to a high state. At that time, the counter string output lines have stabilized and are latched by U22 and U30B into the counter latches. Also, the signal to be counted is again allowed to flow uninhibited to the counter string. The latched counter data is then read one byte at a time by the 3497A controller. When the last byte is read, the register 6 read strobe clocks U22 and causes the counter latches to return to a sampling state. Thus the signal to be counted is held briefly enough not to destroy it, but long enough to stabilize the counter string output.

When handling low-frequency inputs, interrupts are particularly useful. As an example, the counter can be configured to interrupt on measurement complete and then be triggered to do a period measurement. While waiting for the counter to interrupt it, indicating measurement completed, the 3497A can perform other tasks. After receiving the interrupt, the counter result can be read by the counter interrupt service routine. The status and interrupt section provides counter function status and interrupt handling circuits. The status section contains a dual D flip-flop. One half latches when a measurement is completed and the other half latches when an overflow has occurred. This information is sent to various parts of the counter including the interrupt section. If one of these conditions occurs and the interrupts are enabled, then the interrupt section activates the digital interrupt line.

The output line basically consists of an optical isolator and jumpers for configuring the line. It can be configured to operate in an isolated or nonisolated mode. If the nonisolated mode is selected, a pullup voltage is also enabled. Another jumper selects positive or negative true logic. The output line changes logic levels whenever a measurement complete or overflow occurs, independent of interrupt commands.

The counter may be used with the digital input and analog multiplexer plug-ins to create additional system features. Multiplexing inputs to the counter plug-in using the 44421A analog multiplexer plug-in allows up to 30 readings per second using the HP-85 Computer as the controller. This is achieved by having the counter output line externally increment the analog relays and placing the counter in an internal trigger mode.

Expansion from five to forty counters operating via SRQ (service request) can be accomplished easily with the addition of digital input plug-ins. Since SRQ capability is available only in the 3497A and only five slots are in the 3497A, only five counters can have direct SRQ capability. Additional counter plug-ins can operate via SRQ by placing digital input plug-ins in the 3497A and counter plug-ins in 3498A Extenders, and then connecting each counter output line to a digital input line. Up to forty counters can interrupt the

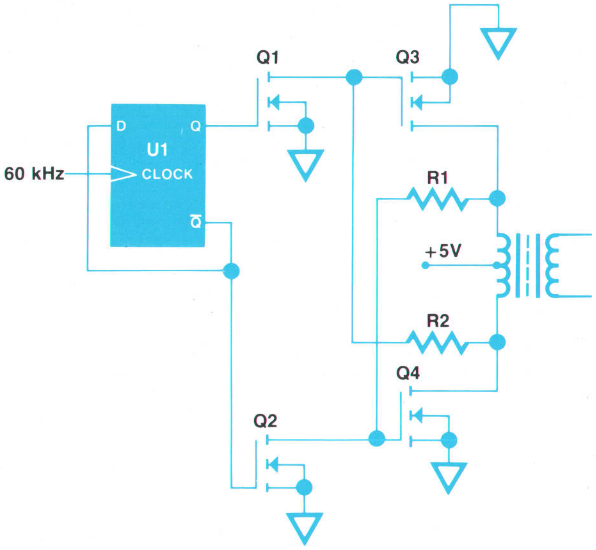


Fig. 5. *Simplified schematic of the dc-to-dc converter power supply used in the voltage and current D-to-A plug-ins.*

3497A since each digital input plug-in handles up to eight interrupts and up to five such plug-ins can be inserted in the 3497A. This method uses the counter output line as an interrupt line that changes level whenever a measurement is completed or an overflow occurs.

Voltage D-to-A Converter

The programmable dual-output digital-to-analog (D-to-A) plug-ins for the 3497A system, a 13-bit voltage output assembly (44429A) and a 12-bit current output assembly (44430A), provide analog outputs that can be used as precision power supplies and references for automated device parameter testing. When more output power is necessary, the D-to-A plug-ins can be used to program other power supplies. In control applications, the current output can be used in several standard process control loops. The voltage output can be used for 0-10V control interfaces. Alarm and trigger setpoints can be programmed with the voltage output plug-in.

The voltage output D-to-A plug-in has two identical, individually isolated and programmed output channels. Each output covers a range of −10.2375V to +10.2375V with 2.5-mV resolution and a maximum output current of 15 mA. There are gain and offset calibrations for each channel. For most cases, these calibrations can be made on easily accessible points at the rear of the plug-in without having to remove the plug-in from the 3497A.

The voltage D-to-A plug-in has three basic parts: the interface to the 3497A mainframe and the two output channels. Each channel has an isolation network and latches to store the output code received from the 3497A. This code is transferred simultaneously to a 12-bit multiplying D-to-A converter and to a polarity amplifier that controls the sign of the reference being applied to the converter and hence the sign of the output voltage. The output stage buffers the output of the D-to-A converter and implements a remote sense. Remote sensing is used to compensate for voltage drop in the source leads. The power supply is a dc-to-dc converter which provides isolation and transforms the 5V supplied by the 3497A into ±18V, ±15V and +5V.

Each channel of the voltage output is isolated from chassis ground and the other channel by using optical isolators. Power and ground isolation is provided by a shielded transformer. This isolation reduces the problem of ground loops and enables the output to be connected to a load that can be as much as 100V above or below the 3497A chassis ground potential. Since the output channels are individually isolated, they may be connected in series to obtain a wider output range.

Power transfer was a very critical part of the D-to-A design. The power required by a D-to-A plug-in from the 3497A mainframe had to be minimized to be compatible with the other plug-ins. This demanded an efficient dc-to-dc converter to transfer the power. Because each channel requires its own power supply, space and circuit complexity had to be minimized. The dc-to-dc conversion circuit in Fig. 5 complies with the space, efficiency, and noise requirements.

During the first part of the switching cycle, the gate of Q1 is at 5V, turning it on, and Q3 is turned off with its gate at 0V. With Q1 on, Q2 is turned off and the gate of Q4 is floating since Q3 is off. Q4 will conduct current because of the voltage existing at the top of the transformer connected through R1 to the gate of Q4. The current flowing through the transformer into Q4 induces 10V at the gate of Q4, enabling the transistor to achieve its lowest resistance. In the second half of the cycle U1 changes state, turning off Q1 and turning on Q3. As Q3 is turned on, Q4 begins to turn off and shuts off the current flowing in the primary of the transformer. When the transformer field collapses, a positive voltage is induced at the drain of Q4 and the gate of Q2. This voltage turns Q2 on and causes current to flow in the opposite direction in the transformer primary. The rest of the second half of the cycle is the same as the first half. The feedback from the drain to the gate has the advantage that a higher voltage is applied at the gate to lower the FET's on resistance and since one transistor is turned on by the other one turning off, there is no chance of both transistors being on at the same time. This technique results in an efficient (90%) transfer of power at full load. Because the transformer is center-tapped, it can be bifilar-wound to reduce coupling from primary to secondary. Both windings are shielded to further reduce coupling. The 60-kHz input to U1 sets the power supply switching rate at 30 kHz. This frequency is used because it is an integral multiple of both 50-Hz and 60-Hz power line frequencies. This enables the system voltmeter to filter out the noise from the switching supply by integrating over one power line cycle.

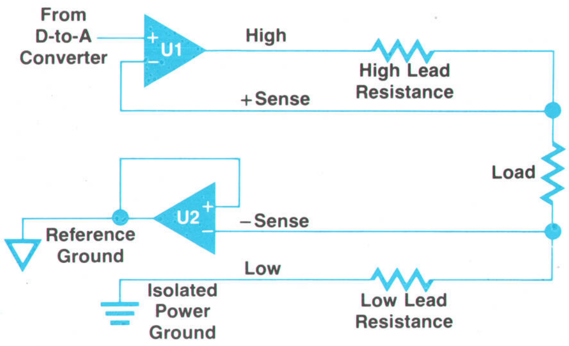


Fig. 6. *Output stage and remote sense connections for voltage D-to-A converter plug-in.*

The output stage of the voltage D-to-A plug-in supplies an output current up to 15 mA and adds remote sensing capability to the output. In addition, the output stage can withstand a short-circuited output indefinitely. The remote sense on the output, when connected directly to the load, allows the output stage to compensate for IR drops in the source leads. A voltage drop of up to 1.5V in the high source lead and a drop of 0.5V in the low lead can be accommodated. To remote sense the high lead, the output source is configured as shown in Fig. 6. The output voltage of the multiplying D-to-A converter is fed into the noninverting input which is connected to the same side of the load as the high source lead. This effectively configures the output source as a unity gain amplifier with the source lead resistance now a part of the source resistance of the output buffer. Remote sensing of the low lead is done somewhat differently. The potential of the load connected to the low source lead is measured with the low sense circuit which is a unity gain amplifier that drives the ground reference of the multiplying D-to-A converter to equal the low side of the load.

Programming of the voltage D-to-A plug-in is straightforward and simple. To program the unit, the character string AOn1,n2,n3 is sent to the 3497A mainframe. AO stands for analog output. Integer n1 is the plug-in's slot number, integer n2 is the output channel selector (0 or 1) and integer n3 designates the desired output voltage in millivolts and can be either positive or negative. Units of millivolts are used for ease of programming and do not always exactly represent the actual output voltage because the output resolution is 2.5 mV. The actual voltage output is the multiple of 2.5 mV nearest to the programmed value.

Current D-to-A Converter

The current output D-to-A plug-in is very similar to the voltage output plug-in. It also has two identical, individually isolated output channels with the same 3497A interface and power supplies as the voltage output. Unlike the voltage output, the current output is unipolar, so the resolution is 12 bits. The output range can be selected by a jumper for either 0 to 20.475 mA with 5-μA resolution or for 4 to 20.38 mA with 4-μA resolution. The compliance voltage, or maximum voltage that the current source can drive, is 12V. Calibration, as for the voltage output plug-in, can be done under most conditions without removing the plug-in from the 3497A.

The output stage of the current D-to-A plug-in, shown in Fig. 7, converts the voltage from the D-to-A converter into a current. It is the major difference between the voltage and current D-to-A plug-ins. The voltage-to-current conversion is performed by amplifier U1, R5, and Q1. Q1 is a low-leakage p-channel JFET that is used to control the output current flowing through sense resistor R5. The resistive network of R1 through R4 is used to set the output range to either 4-to-20-mA or 0-to-20-mA. The network with Q2 and Q3 serves a dual purpose. During power-up or power-down, U1 is not able to control the gate voltage of Q1. Because Q1 is a depletion mode device, it will allow current to flow into a load connected across the output terminals when there is no gate voltage. This creates the possibility that a controllable device such as a valve or motor may be operated unexpectedly when the 3497A is turned on or off. To avoid this the 30V zener diode CR1 prevents any base current from flowing into Q3 until the supplies are within 80% of final value. Q3 is saturated during normal operation so it will not reduce the compliance voltage significantly. The JFET Q2 regulates the voltage across Q1. When the voltage at the drain of Q1 and the gate of Q2 goes below −13V, Q2 will begin to conduct current. This reduces Q3's base current, causing it to come out of saturation and operate in the linear region. Any voltage not dropped across Q1 or the load will be dropped across Q3. This limits the power dissipated by Q1 and also buffers the output circuit from negative voltages that are accidentally applied to the output. Positive voltages are blocked by diode CR2.

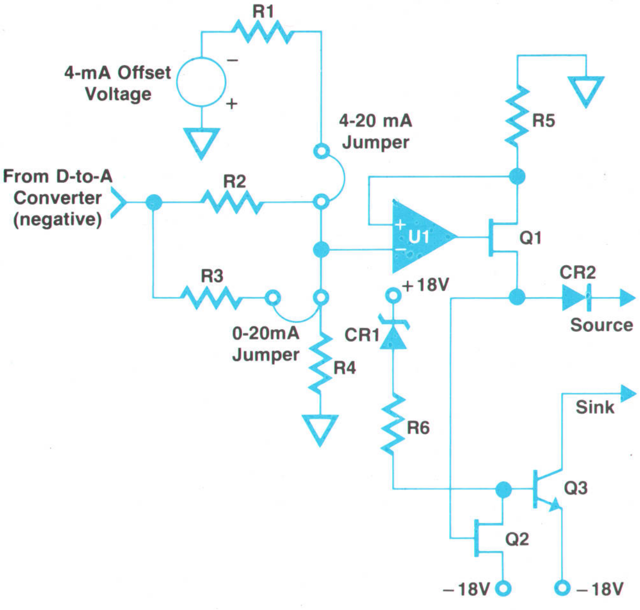


Fig. 7. *Current output stage for the 44430A current D-to-A converter.*

Programming of the current output D-to-A plug-in is optimized for control loop applications in the 4-to-20-mA range. The character string sent to the 3497A for the current output is the same as for the voltage output, AOn1,n2,n3. The only difference is that the integer n3 is programmed in units of 0.01% of output range. If a negative n3 is received the sign is ignored. As an example, in the 4-to-20-mA range, the output is 4 mA for n3=0 or 0%. Likewise, for n3=10000, corresponding to 100%, the output is 20 mA. This programming is parallel to that of a proportional control device such as a valve, where 4 mA causes a 0% opening and 20 mA causes a 100% opening. In all cases the actual output current is the multiple of 0.025% of the current range nearest to the programmed value.

Strain Gauge/Bridge Assemblies

Any mixture of ¼, ½, or full-bridge circuits can be terminated on these plug-ins. Connections are made using two, three, or four wires plus shield. The assemblies use an external supply and either the voltmeter module in the 3497A or an external voltmeter such as the 3456A. The supply requirements are 0 to ±5.4 Vdc and 25 mA/channel for the 44427A or 8 mA/channel for the 44427B.

The external supply is always applied, never switched, to eliminate errors caused by dynamic heating and cooling of the gauge. The voltage is measured on each strain gauge/bridge plug-in, so strain accuracy is independent of long-term supply voltage changes.

Manual adjustments are eliminated because the initial voltmeter readings for bridge excitation and bridge unbalance can be processed by the system controller to solve the bridge equation. A system computer is required to compute strain. Computer subroutines are available in 3054A and 3054C systems to measure bridge output and excitation supply, compute strain, and do shunt calibration.

The plug-ins are split into two 10-channel blocks: 10 measurement channels and 10 diagnostic channels. All can be addressed and displayed on the front panel of the 3497A. The diagnostic channels allow shunt calibrations, lead-wire resistance measurements, and gauge leakage, supply voltage, and internal half-bridge tests.

Patricia A. Redding

Pat Redding joined HP in 1979 as a development engineer and was responsible for the design of the counter plug-in used in the 3497A. She is a native of Indianapolis, Indiana and attended Purdue University, earning a BSEE degree in 1979. Pat is married (her husband is also an engineer and works at HP) and lives in Loveland, Colorado. When not busy with graduate studies in electrical engineering at Colorado State University, Pat enjoys hiking, bicycling, and playing tennis.

Richard L. Hester

Rick Hester was born in Jacksonville, Florida and graduated from the University of Florida with a BSEE degree in 1979. He then joined HP and was responsible for the design of the voltage and current D-to-A plug-ins used in the 3497A. Rick is married and lives in Loveland, Colorado. Outside of work and studies for an MSEE degree at Stanford University through an internal HP program, he is refinishing the basement of his home and enjoys hiking, swimming, and camping.

ABRIDGED SPECIFICATIONS

HP Model 3054A Data Acquisition/Control System

SYSTEM CONFIGURATION: Basic system includes 3437A System Voltmeter (described in February 1977 issue); 3456A Digital Voltmeter (described in April 1981 issue); 3497A Data Acquisition/Control Unit (described on page 9) with optional plug-in assemblies (described on page 16); a 76.2-cm rack cabinet with filler panels, fan, and power outlets; and the system documentation and software. One of four computer configurations is needed to complete the system.

1. HP-85A Computer with 82937A HP-IB Interface, 00086-15003 I/O ROM, 82936A ROM Drawer, and 82903A Memory Expansion Module.
2. HP 9825T Computer with 98034B HP-IB Interface.
3. HP 9835A Computer with 98034B HP-IB Interface and 98332A I/O ROM.
4. HP 9845T Computer with 98034B HP-IB Interface and 98412A I/O ROM.

SYSTEM OPERATION: The times given below are approximate. Actual times will vary depending on the computer, program structure, and variations between system instruments. A complete measurement will consist of four tasks: 1) setup, 2) close a channel, 3) take a reading, and 4) transfer the reading to the computer. After the measurement the computer will do some data manipulation and output.

The take-a-reading time includes triggering the voltmeter, taking the reading, and storing it in the DVM's buffer memory. The transfer time includes transferring the reading from the DVM to the computer. With the 3437A DVM, these two times are combined because only the computer can store the readings.

SETUP DVM TIMES (ms):

	85A	9825T	9835A	9845T
3456A	88	66	86	86
3437A	47	6	19	19
DVM Assembly (optional) for 3497A	106	78	92	92

CLOSE CHANNEL TIMES (ms/channel):

	85A	9825T	9835A	9845T
Relay Assembly (Option 010/020)	37	10	26	26
Digital Input/Interrupt Assembly (Option 050)	63	15	55	55
Actuator Digital Output Assembly (Option 110)	44	14	36	36

CLOSE CHANNEL TIMES FOR EXTERNAL INCREMENT MODE (ms/channel, computer independent):
Normal (AE1): 3
Fast (AE2): 2

3456A READ TIMES (ms/channel): These times were taken on a manual range with auto-zero, math, filter, and display off.

Function	Resolution					
	6½ digits		5½ digits		4½ digits	
	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz
Vdc	25	20.8	5.55	4.76	3.44	3.03
Ohms, 100Ω through 10 kΩ ranges	25	20.8	5.55	4.76	3.44	3.03
Vac	91	83				

3497A DVM READ TIMES (ms/reading): These times were taken with auto zero off.

	Resolution		
Line Frequency	5½ digits	4½ digits	3½ digits
50 Hz	25	6.02	4.00
60 Hz	20	5.00	3.33

3437A READ AND STORE TIMES (ms/reading):
The 3437A DVM uses the computer buffer memory to store the readings, therefore the read and transfer times have been combined. The readings from the 3437A can be transferred to the computer in two different output modes.

Output Mode	Transfer Mode	85A	9825T	9835A	9845T
ASCII	Single Reading into variable	38.00	4.10	26.00	21.00
	Multiple Readings into array	38.00	4.10	12.00	7.80
Packed	Multiple Readings into string variable	1.40	0.30	0.86	0.95
	Multiple Readings with buffered transfer into string	0.24	0.39	0.22	0.24

The time to unpack readings is not included in these times.

3456A TRANSFER TIMES (ms/channel):
The reading in the 3456A can be transferred to the computer in two different output modes.

Output Mode	Transfer Mode	85A	9825T	9835A	9845T
ASCII	Single Reading into variable	53	16	42	31
	Multiple Readings into array	53	16	30	23
Packed	Multiple Readings into string variable	11	8.8	9.5	9.6
	Multiple Readings with buffered transfer into string	9.7	9.2	8.4	8.3

The time to unpack readings in the computer is not included in these times.

DVM ASSEMBLY FOR 3497A TRANSFER TIMES (ms/reading):
The reading in the DVM Assembly can be transferred to the computer in two different output modes. Times are given for single reading transfers or multiple reading transfers.

Output Mode	Transfer Mode	85A	9825T	9835A	9845T
ASCII	Single Reading into variable	35	5.5	31	20
	Multiple Readings into array	35	5.5	19	13
Packed	Multiple Readings into string variable	3	2.2	3	3
	Multiple Readings with buffered transfer into string	2.2	2	2	2

DATA MANIPULATION AND OUTPUT: Since the 3456A DVM and DVM Assembly for the 3497A have internal storage capability, data can be manipulated or output by the computer during the measurement sequence to shorten the test time.

NUMBER OF CHANNELS: The 3054A System can accommodate up to 1000 analog channels and 1360 digital channels. The 3497A can hold up to five assemblies and each 3498A Extender can hold ten more assemblies. To achieve a maximum of 1000 analog channels requires a 3497A and five 3498A Extenders. To add the maximum 1360 digital channels requires an additional eight 3498A Extenders. Each 3497A and a maximum of 13 extenders can be used on one HP-IB address.

TEMPERATURE PERFORMANCE: The temperature specifications apply to the 3054A system temperature measurements taken by one of the voltmeters with inputs switched by the 3497A.
REFERENCE JUNCTION COMPENSATION ACCURACY: (23°C ± 5°C): ± 0.3°C.
TEMPERATURE COEFFICIENT: (0° to 18°C, 28° to 50°C): ± 0.03°C/°C.
TEMPERATURE SENSING DEVICE OUTPUT: 100 mV/°C; 2.5V at 25°C.
THERMOCOUPLE TYPES: J, K, T, E, R, S, B, Nicrosil-Nisil (14 AWG), Nicrosil-Nisil (28 AWG).

GENERAL:
WEIGHT (basic system): 104.4 kg.
SIZE (HWD of rack cabinet): 909.6 × 621.6 × 808.6 mm.
OPERATING RANGE: 0 to 50°C, 98% relative humidity at 40°C.
POWER: 100, 120, 220, 240V +5%, −10%; 48-66 Hz; 252 VA, maximum.

PRICE IN U.S.A. (basic system), $10,685.

HP Model 3497A Data Acquisition/Control Unit

TIMER/REAL-TIME CLOCK:
ACCURACY: ±(0.005% of time + 0.1 s) for all functions except timer output mode which has ±(0.02% of time) accuracy.
POWER FAILURE PROTECTION: Battery backup for >24 hours for all functions except timer output mode.
RESOLUTION: 1 s for all functions except timer output mode which has 100-μs resolution.

MODE: (All modes can be used simultaneously)

	Maximum Time	Output
Real Time	1 year	--
Elapsed Time	1,000,000 seconds	--
Time Alarm	24 hours	HP-IB SRQ
Time Interval	24 hours	50-μs TTL pulse + HP-IB SRQ
Timer Output	1 second	16-μs TTL pulse

DVM ASSEMBLY (Option 001):
VOLTMETER RANGE/RESOLUTION (5½ digit)/TEMPERATURE COEFFICIENT (±(% reading + number of counts)/°C; 0 to 18°C, 28 to 55°C):

0.1V	1 μV	0.00025 + 0.15
1.0V	10 μV	0.0002 + 0.02
10.0V	100 μV	0.0002 + 0.01
100.0V	1 mV	0.00025 + 0.03

VOLTMETER MEASUREMENT ACCURACY (±(% of reading + number of counts), auto zero on): 0.003 + 3 for 0.1V range, 0.002 + 1 for all other ranges; 24 hours, 23°C ±1°C, 5½-digit display.
NOISE REJECTION (5½-digit display, one line cycle integration period):
ac NMR: 60 dB, 50 or 60 Hz.
ac ECMR: 150 dB, 50 or 60 Hz.
dc ECMR: 120 dB.
MAXIMUM INPUT VOLTAGE:
High to Low: 120V peak.
Low to Guard: 170V peak.
Guard to Chassis: 170V peak.
CURRENT SOURCE:
Range/Accuracy (24 hours, 23°C ±1°C)/Temperature Coefficient (per °C; 0 to 18°C, 28 to 55°C):

10 μA	1.25 nA	0.25 nA
100 μA	12.5 nA	2.5 nA
1 mA	125 nA	25 nA

Compliance: >15V.
Isolation voltage: 170V, peak.
MAXIMUM READING RATE (readings/s): Auto zero off (turning auto zero on halves the reading rate).

Digits Displayed	60-Hz Operation	50-Hz Operation
5½	50	40
4½	200	166
3½	300	250

READINGS PER TRIGGER: 1 to 999.
DELAY: 0 to 99.9999 s in 100-μs steps with 5% +200-μs accuracy.
BUFFER SIZE:
Packed Format: 100 readings.
ASCII Format: 60 readings.

AUXILIARY INPUTS/OUTPUTS:
EXTERNAL TRIGGER: TTL compatible, 50-ns minimum pulse width.
EXTERNAL INCREMENT: TTL compatible, 50-ns minimum pulse width.
BREAK-BEFORE-MAKE SYNC: TTL compatible. This input/output terminal serves as a break-before-make synchronizing signal to the 3497A and other equipment. A low level indicates that a channel is closed. The 3497A will not close any additional channels until the line is sensed high and the line will float high when all channels are open.
VOLTMETER COMPLETE OUTPUT: TTL compatible, 300-μs pulse width.
CHANNEL CLOSED OUTPUT: TTL compatible, 500-μs pulse width.
TIMER OUTPUT: TTL compatible.

GENERAL:
SIZE (HWD): 190.5 × 428.6 × 520.7 mm.
WEIGHT (net, with assemblies in all slots): 20.4 kg, maximum.
OPERATING TEMPERATURE: 0 to 55°C.
HUMIDITY: To 95% at 40°C, except as noted.
SHOCK: 30g, 11-ms sine wave on each of six sides.
VIBRATION: 5 to 55 Hz at 0.38-mm peak-to-peak excursion.
POWER REQUIREMENT: Switch selection of 100, 120, 220, or 240V, ±10%; 48-66 Hz 150 VA.

PRICE IN U.S.A.: Model 3497A Data Acquisition/Control Unit, $2450.
Option 001 DVM and Current Source, $1500.

MANUFACTURING DIVISION: LOVELAND INSTRUMENT DIVISION
815 Fourteenth Street, S.W.
Loveland, Colorado 80537 U.S.A.

ABRIDGED SPECIFICATIONS

HP Model 9915A Modular Computer

FEATURES:
FRONT-PANEL KEYS (all keys can be disabled by appropriate program statements): Eight special function keys (four shifted keys), **AUTO START** key to load and execute "Autost" file, and **SELF TEST** key to initiate self-test.
FRONT-PANEL LIGHTS: Eight LEDs (four green and four yellow) to annunciate label area, **RUN** to indicate running BASIC program, **SELF TEST** to indicate self-test mode, and power **ON**.
LABEL AREA: 55-by-53.5-mm area where a plastic insert can be installed to label the special function keys and LEDs.
EPROM CARD: A socketed printed circuit board to allow up to eight EPROMs (2516, 2716, or 2732) to be used to store up to 32K bytes of application programs.
ROMs: Two ROMs (I/O and Program Development) are included in the standard 9915A. Four more option ROMs can be installed.
I/O SLOTS: Three standard HP-85A I/O card slots are available in the back.
CLOCK/TIMERS: Time is maintained in seconds since MASTER RESET along with year and day in year. Three timers can be programmed to generate end-of-line interrupts periodically, at intervals from 1 ms to 99,999,999 ms (1.16 days) with 1 ms resolution.

READ/WRITE MEMORY: 16K bytes, standard. Expandable to 32K bytes.

DYNAMIC RANGE:
REAL PRECISION: −9.99999999999E499 to −1E−499,0, and 1E−499 to 9.99999999999E499.
SHORT PRECISION: −9.9999E99 to −1E−99,0, and 1E−99 to 9.9999E99.
INTEGER PRECISION: −99999 to 99999.

BUILT-IN FUNCTIONS: Nineteen mathematical, nine trigonometric, four logic, and six relational functions are included in an enhanced BASIC language set.

GENERAL:
SIZE (HWD): 145 × 213 × 446 mm.
WEIGHT: 4.54 kg, net.
OPERATING TEMPERATURE: 0° to 55°C.
HUMIDITY: 95% relative humidity, 0 to 40°C.
POWER: 100, 120, 220, 240V ±10% switch selectable, 48-66 Hz, 49 VA maximum.

PRICE IN U.S.A.:
Model 9915A Modular Computer, $1675.
Option 001 HP 200 Tape Drive, $425.
Option 002 Operator Interface, $350.

MANUFACTURING DIVISION: DESKTOP COMPUTER DIVISION
3404 E. Harmony Road
Fort Collins, Colorado 80525 U.S.A.

Desktop Computer Redesigned for Instrument Automation

Combining the system development ease of a desktop computer with the configuration flexibility of a board computer provides the instrumentation system designer with a new alternative for automation.

by Vincent C. Jones

UNTIL NOW, COMPUTERIZING the control of an instrumentation system has forced the designer to choose between a desktop computer with low development cost but high unit cost, and a board or box computer, which can provide the low unit cost, but requires far more development effort. A reasonable compromise is now available in the form of the 9915A, HP's first modular desktop computer (Fig. 1). This product provides the development ease of a desktop computer to such diverse applications as production test automation, embedded intelligence in OEM (original equipment manufacturer) systems, and custom controllers for specialized applications. Unit costs are competitive with off-the-shelf board computer systems while applications software development is as easy as using an HP-85 Personal Computer.[1] Applications software can be designed, programmed, and debugged on an HP-85 because inside the basic 9915A is an HP-85—without the keyboard, display, tape drive, or printer.

Fig. 1. *The HP Model 9915A Modular Computer is a powerful desktop computer in a rack-mountable package designed for industrial environments. This low-cost computer is easy to use for measurement automation.*

The ideal production test controller runs only the specific tests required for a particular production line. The user interface is optimized for the operator, not the programmer, and can be as simple as two pushbuttons to start and abort the test and three status lights (test in progress, test passed, and test failed). The standard programmer's keyboard and display are not only unnecessary, they are actually detrimental. Users have gone to the extreme of bolting sheet metal over the keyboards of desktop computers to limit exposure to only the few necessary keys. Others have taken a hacksaw to their equipment rack so the desktop computer would fit in.

Why would anyone go to such lengths just to use a desktop computer? The answer is cost. In many applications, a $10,000 desktop computer is cheaper than a $500 single-board computer when the time and effort required to develop custom hardware and software are taken into account. The ability to buy I/O interfaces off the shelf and communicate with them directly using a high-level language can cut programmer-years from development time and reduce development costs correspondingly. Depending on the level of computer design expertise available, the monetary break-even point between the development cost required to use a modular computer and the alternative cost of using desktop computers can be as high as several hundred units per year.

System Design

Creation of the 9915A consisted of more than simply squeezing an HP-85 into a rack-mountable box. Numerous modifications and additions were required, such as adding LED (light-emitting diode) annunciators to the front panel, revamping the keyboard and CRT display drivers to function over long lengths of cable, and redesigning the power supply to meet the modified loading and environmental conditions.

Nor were the required changes restricted to the hardware realm. A computer like the HP-85 is designed and optimized for ease of program development. The goal is a friendly, totally integrated package. The problem is that an integrated hardware/software system built expressly to meet the needs of the programmer is almost totally crippled when its keyboard, CRT, tape drive, and printer are removed.

Our goal was to maximize the operator interface flexibility of the 9915A without increasing the burden on the

A Unifying Approach to Designing for Reliability

by Kenneth F. Watts

Product reliability was the feature most demanded of the 9915A Modular Computer development team and the most challenging. To achieve greater levels of product producibility and reliability, a new approach is necessary to overcome the weak link in the design cycle—the designer's inability to see into the future and to gather data on production-built units in application at customer sites within the full range of variability caused by time and environment. Obviously, if the designer is aware of all the hazards to be imposed on the product, each can be addressed, and given sufficient resources, resolved. This new approach must combine the best analytic tools for testing product reliability with the philosophy of zero defects and extend the combination into a production-line environment as a problem solving tool and as a monitor of product quality.

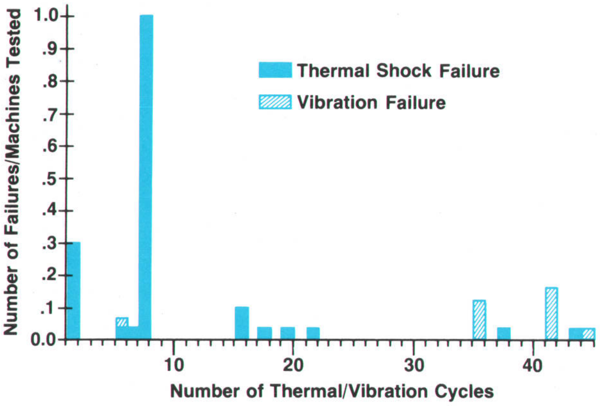


Fig. 1. *Failure rate versus number of thermal and vibration cycles. The data shows that most of the units failed during the seventh thermal cycle and that most vibration-induced failures occurred later in the strife testing.*

The reliability testing technique was suggested by the work of Carl M. Bird at IBM[1], and our own experience at HP's Loveland Instrument Division. Work at these places suggests that the mechanical interconnects in electronic products are the primary source of failure. Attacking this weakness directly with temperature cycling and vibration provides an accurate time-accelerated model of the world outside. Deficiencies in design, process, or material result in early failures while a successful implementation results in no significant life degradation. The essential difference between this strife test and the traditional life test (MIL-STD-217B) is that the strife test's success is measured by the number of problems identified rather than their absence. This difference encourages the design team to search out design, process, and material flaws, and resolve them before they become issues in production.

The implementation of strife test[2] requires a statistically large number of units built by production techniques. This implies that production starts, then pauses while its first output is tested, and then starts again after implementing any changes indicated by the test results. Strife test on the 9915A was performed on forty units to generate 8000 unit-hours of operation quickly.

Testing was conducted in two concurrent activities: temperature cycling and vibration testing. A large environmental chamber, capable of 1°C-per-minute temperature ramps from −20°C to +65°C, was used to contain the units throughout the test. The units were temperature and power cycled while the condition of each unit was monitored by an HP 9835A Computer-controlled data acquisition system. The system initiated and recorded a total of 140,000 self-test sequences and results along with ambient temperature data. Vibration testing was performed daily on an air-driven shake table (10 g peak acceleration at 57 Hz) for 10 minutes on each unit at room temperature outside the chamber. This test required that each 9915A tested load and run a BASIC program from tape. Results were manually taken.

Expectations of the test were threefold: conformance to expected model, actions required to solve problems, and cost. The model of failure distribution indicated that there would be a predominance of early failures as problems surfaced and were solved. The distribution of unit failures with respect to the number of thermal cycles (Fig. 1) supports the assertion that wear-out mechanisms are not commonly invoked in electrical design that is correctly implemented.

The failure data plotted in Fig. 1 shows that a major problem was encountered during the seventh thermal cycle. Further, Fig. 2 shows that most of these failures occurred during a particular

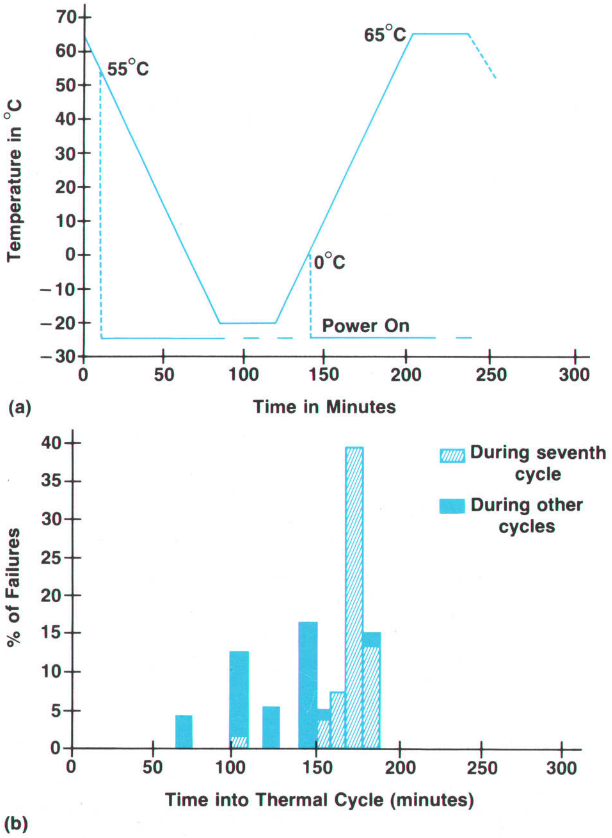


Fig. 2. *(a) Plot of single thermal cycle. (b) Distribution of failures with respect to the part of the thermal cycle when they occurred. As can be seen, most occurred at low temperature and on the rising edge of the cycle. The seventh thermal cycle had a particularly high failure rate due to high humidity conditions caused by local thunderstorms.*

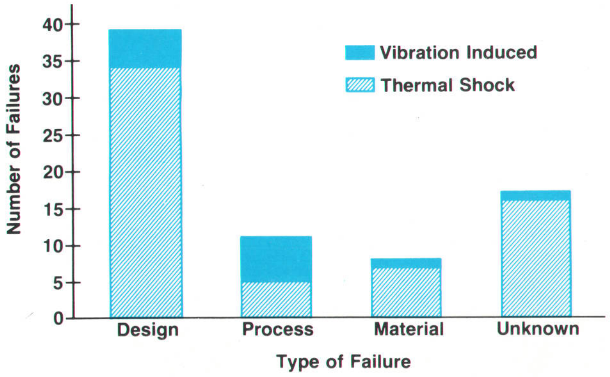


Fig. 3. *Classification of failure types induced by thermal shock and by vibration (a total of 63 thermal shock and 13 vibration failures during initial strife testing of 40 units).*

portion of the thermal cycle. This was a single problem that occurred in 39 units because of condensation on a day when the humidity was unusually high. The solution was to isolate a sensitive node in the power supply and include failure sequence protection. Fig. 1 also shows an increase in late vibration-induced failure. The cause was determined to be tape transport boards working out of their sockets. Reseating the boards solved this problem.

The distribution of failure type (Fig. 3) supported previous experience in new product production. Design-induced failures were predominant. The class of failures that could not be duplicated was the most troublesome, and represents the remaining unanswered question posed by the test. Extensive retesting yielded no further information.

All problems were analyzed with respect to the effects on the production process and design and appropriate solutions were implemented. The nature of these fixes ranged from tightened screws to components added to the printed circuit boards for enhanced reliability.

No units were lost to the test; all 40 were retrofitted with the modifications generated from test results and were shipped as demonstration units to our field sales offices. The time required to perform the test was four weeks. Short-term fixes were in place at the end of that time and production was able to proceed two weeks later.

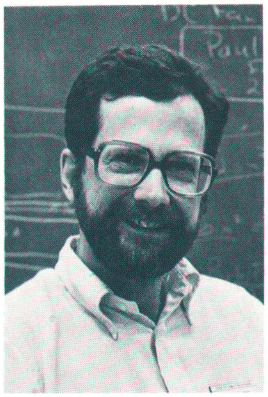
The final step of the 9915A reliability plan was to put a temperature cycling chamber in the production area as an ongoing monitor of material, processes, and effects of production design changes. The only change from the strife test is to limit the temperature cycle to −5°C to +55°C. The same data acquisition system is used to monitor and manage the huge volume of data.

Acknowledgments

The quality assurance group at the Loveland Instrument Division, headed by Craig Walters, plotted the original course for these concepts. Jerry Nelson and Dick Barney provided the guidance and counsel necessary to keep us on track. Jack Murata provided the talented production people: Ellen Anderson, Carl Anderson, Mark Gonzales, Vivian Kaiser, Mark Oman, and Karen Zamora. Bob Bailey and Bruce Young created and performed the test while Dave Sweetser and Bob Gilbert are involved in further improvement of the product in production.

References:

1. C. Bird, "Unit Level Environmental Screening," Proceedings - Institute of Environmental Sciences, May 1980.
2. R. Bailey and R. Gilbert, "Strife Testing for Reliability Improvement," Proceedings - Institute of Environmental Sciences, May 1981.



Kenneth F. Watts

Ken Watts is a native of Minneapolis, Minnesota and attended the University of Minnesota, earning a BSEE degree in 1969. He joined HP's Loveland Division that same year and worked in R&D and production on voltmeters and data logging systems (Models 3051A, 3052A, and 3495A). Ken transferred to the Desktop Computer Division in 1979 and is the project manager for the 9915A. He is married, has three children, and lives in Loveland, Colorado. Ken is the president of the local homeowners association and an assistant Scoutmaster for the Boy Scouts of America. He enjoys camping with his family, singing in his church choir, and landscaping and gardening at his home.

applications programmer. As it turns out, the configuration flexibility of the 9915A actually reduces the complexity of the application programmer's job by simplifying the optimization of the operator interface for a particular application. The 9915A can be used as a desktop computer to solve engineering problems, or can be stripped down and buried inside a product to interpret control-panel pushbutton commands.

This level of applications flexibility was attained by adding seven major capabilities to the HP-85 during the process of repackaging it.

- User-definable front panel. A user printable/replaceable plastic label area is flanked by the four HP-85 special function keys on the left and four pairs of yellow and green LEDs on the right.
- Total matrix control for remote keyboard options. A BASIC program can take over remote keyboard interrupt handling, providing up to 76 keyboard matrix crosspoints with any desired interpretation. The status of the remote keyboard may also be queried at any time to determine what crosspoint, if any, is currently activated.
- Total display control for external CRTs. A BASIC program can position the next output anywhere on or off the screen of an external CRT, display any character or string of characters with or without control code interpretation, select which sixteen-line segment of the 64-line display memory is displayed, determine the current cursor and window positions, and read back any of the contents of the display memory.
- Modular architecture options. The tape cartridge drive and external operator interface are optional. I/O flexibility is available in the full family of optional HP-85 ROMs (read-only memories) and plug-in interfaces.
- Environmental hardness. A maximum internal temperature rise of 5° C means no special cooling considerations are required for rack mounting in industrial environments. The 9915A meets rigorous environmental requirements including operation over the full industrial

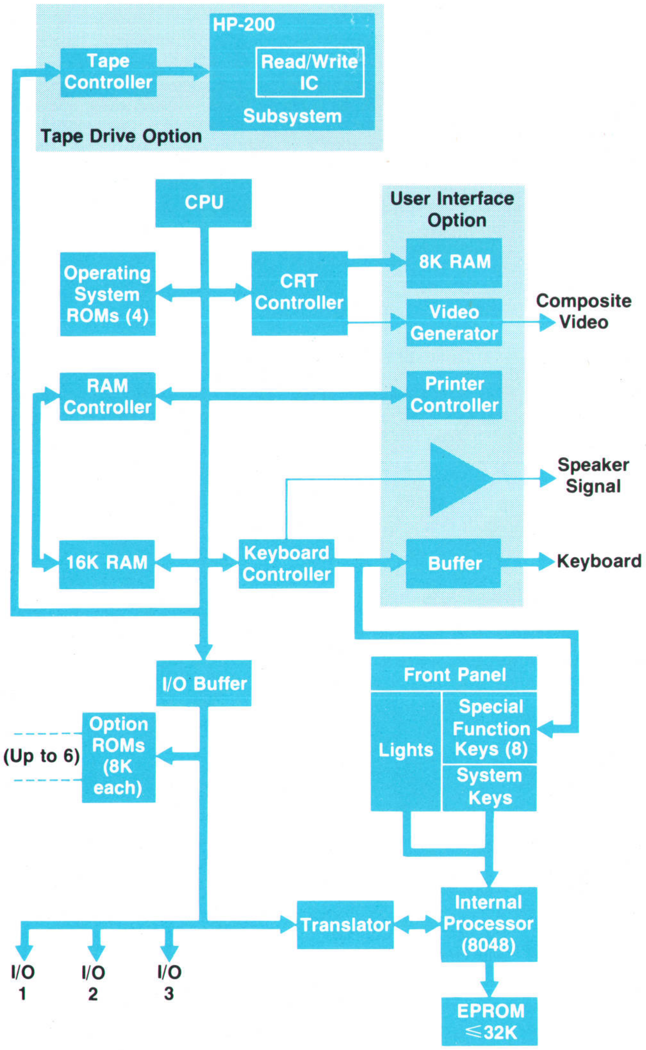


Fig. 2. *The 9915A uses the architecture of the HP-85 partitioned as shown in the above block diagram.*

temperature range of 0° to 55° C (except for magnetic media) and immunity to humidity extremes (5 to 95% relative humidity at 40°C), ac line transients (up to 1 kV), electrostatic discharge (up to 15 kV), shock (30 g), vibration (0.38-mm amplitude from 5 to 55 Hz) and magnetic fields (up to 10^{-4} tesla).

- Extensive self-test capability. A front-panel pushbutton activates the automatic confidence test procedure. Passage of the full battery of tests provides better than 98% confidence of system integrity.
- Tamper-proof mass storage. An internal plug-in card holds up to 32K bytes of EPROM (electrically programmed ROM) mass storage, providing the equivalent of up to 126 tape records for programs and binary programs. At power-on or whenever the **AUTO START** button on the front panel is pressed, the computer can automatically load and run a program from either EPROM or tape.

All of these features were added while maintaining 100% compatibility with the HP-85 desktop system. Any program written for the HP-85 (except those that directly access the internal printer) will operate identically on the 9915A. The 9915A can use any 80-Series computer option ROM or plug-in I/O module because it not only uses the same system hardware but also the same operating system firmware (actually there is a one-byte difference; the subroutine that turns off the display in the HP-85 during tape and printer operation is not used in the 9915A).

The HP-85 can be used as a development system for the 9915A by installing the Program Development ROM (98151A). The only differences are in hardware-dependent features like EPROM program storage (the HP-85 uses tape instead) and front-panel LED annunciators (which are displayed on the HP-85 CRT). For real-time applications where the longer execution time required for emulation could affect performance, the 9915A can support its own program development when equipped with a CRT display, keyboard, mass storage, and external printer.

System Architecture

To understand the 9915A, it is first necessary to understand the HP-85. The HP-85 is a personal computer with a complete set of integrated peripherals: alphanumeric/graphics CRT display, 32-column thermal printer, full ASCII keyboard, random-access tape drive, three event timers, one elapsed-time timer, and a programmable audio oscillator. In addition to the peripherals, the HP-85 contains a 32K-byte ROM operating system, 15K bytes of user memory, and four option slots in the back. These slots allow for the addition of 16K bytes to the user memory, system software expansion via ROMs, and system hardware expansion via interface cards.

The plug-in ROM drawer can contain up to six 8K-byte ROMs which include the I/O ROM for general interface control, the matrix ROM for easy array operations, the Plotter/Printer ROM for enhanced graphics capabilities, the Mass Storage ROM for flexible disc operations, the Assembler ROM for user development of BASIC language extensions, and the Program Development ROM for emulating the 9915A on an HP-85. Interfaces currently available include HP-IB,* Serial (RS-232-C and 20-mA current loop), GPIO (16 bits bidirectional plus an extra 16 bits of output only), and binary coded decimal (BCD).

The HP-85 Computer is implemented with LSI (large-scale integration) circuitry. The CPU, ROM memory, dynamic RAM (random-access memory) control, and peripheral controllers are implemented on individual LSI chips.[2] The architecture, system operation, and other design features of the HP-85 were described in detail in the July 1980 issue of this journal.

Internally, the 9915A contains the same LSI chips as an HP-85. Missing are the HP-85's printer, CRT, keyboard, and tape drive. (The tape drive can be added with Option 001.) The 9915A also includes a built-in interface card not present in the HP-85. This interface controls the 9915A front panel and EPROM mass storage. It also controls the extensive self-tests available on the 9915A.

External interface cards communicate with the HP-85 system bus through a translator chip.[3] This component maps an interface card into one of eight address pairs in the I/O address range. The internal interface of the 9915A works in the same way but it is mapped into a different set of addresses.

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*Hewlett-Packard's implementation of IEEE Standard 488 (1978).

Designing Testability and Serviceability into the 9915A

by David J. Sweetser

Throughout the conceptual and design phases of the 9915A project, considerable resources were devoted to creating a product with advanced testability and servicability features. Whereas diagnostic software is the typical primary means of providing self-diagnostics, the design of the 9915A incorporates, in addition to diagnostic software, many hardware test features, ease of human interaction, and the ability to test and diagnose problems by using automated testing.

Testability is enhanced primarily by the inclusion of an exhaustive built-in self-test that provides two main benefits:

- Production testing of the 9915A is greatly simplified. For the main board (containing most of the LSI parts), this self-test is activated by the automatic board tester. If the board passes self-test, then further testing simply involves testing those circuits that are not testable by self-test. If a board fails, then the board tester communicates with the board to learn what failed. After a 9915A is fully assembled, this same self-test is activated during instrument turn-on, oven testing and final testing.
- Self-test of the 9915A can be activated by a front-panel **SELF TEST** key. This gives the user a high degree of confidence that if the self-test passes the 9915A is fault-free. This is especially valuable in the complex control systems for which the 9915A is intended, because the self-test permits isolating the problem to the 9915A or the remaining system elements.

As would be expected, self-test is a key element in providing enhanced serviceability. Self-test can isolate a problem to a particular bad IC. However, self-test is not the entire answer. For example, if the 9915A's CPU or the ROM containing the self-test code is bad, then self-test may never execute. To supplement the self-test, the 9915A incorporates a service mode. Here the primary tool is signature analysis because this technique provides quick and unambiguous diagnostics, whether at an automatic board tester, on a technician's bench, or in the field

Just as self-test is used both in production testing and by the user, the features of the service mode are also multipurpose. If the board tester detects a bad board, it activates the service mode to diagnose the problem. Likewise, line technicians also use the service mode for troubleshooting. HP field repair or OEM repair can also use these same techniques.

The 9915A uses the custom chip set of the HP-85. This chip set is hereafter referred to as the primary chip set. The 9915A also incorporates a second processor, an 8048 microcomputer. The primary purpose of the second processor is to perform such functions as control of the front-panel LEDs, monitoring of the **AUTO START** and **SELF TEST** keys, and reading of the EPROM. However, an additional function of the 8048 is to support self-test and the service mode, specifically signature analysis.

The normal communications path (see Fig. 1) between the 8048 and the CPU is a translator chip containing several registers. However, two additional paths are provided:

1. The second processor controls the reset lines to all of the chips in the primary chip set.
2. The second processor can strobe the clock for the primary chip set to synchronize it with its own clock.

The results of this are far-reaching. The 8048 can selectively enable chips within the primary chip set while providing a window start/stop signal for signature analysis. A user usually samples data on the CPU bus by using the CPU clock. Stable signatures are assured by the 8048's strobing the clock synchronization input to the CPU clock circuit.

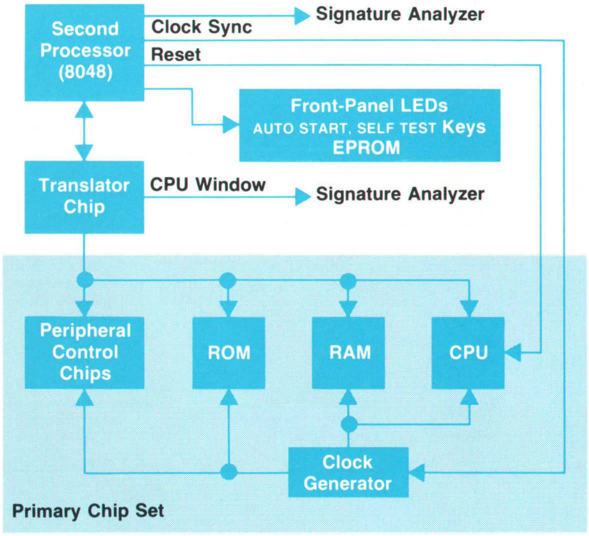
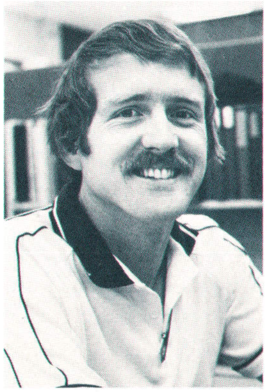


Fig. 1. *Communications path between the primary LSI chip set in the 9915A and the second processor. This processor controls front-panel functions and supports self-test and the service mode.*

In addition to these control functions, the second processor provides a simple operator interface to these functions. In the service mode (accessed using an internal jumper), the 8048 displays on the front-panel LEDs which signature analysis test is presently being executed. The user presses the **AUTO START** key to step to the the desired test, and connects the signature analyzer as directed for that particular test.

The tests start off simply: the entire primary chip set is reset. Because the bus is precharged and is static, the primary diagnostic tool is a DVM. Bus pins that are erroneously pulled high or low show up easily in this test. Typically, application of heat and/or cold quickly identifies the offending chip.

Again using the **AUTO START** key, the user can step the second processor to a test where the CPU is allowed to free-run with the primary chip set RAM and ROM disabled. The CPU signature in



David J. Sweetser

Dave Sweetser was born in Woodland, California and attended Harvey Mudd College where he earned the BS (1971) and MS (1972) degrees in engineering. After several years in the aerospace industry he joined HP in 1977. Dave designed I/O components for the HP-85 Computer and the self-test and service features of the 9915A. He is married and lives in Fort Collins, Colorado. Outside of work Dave and his wife are busy landscaping the home they designed and constructed. He also enjoys backpacking, cross-country skiing, snow camping, rafting, bicycling and racquetball.

free-run mode indicates whether or not it is basically functional (although a good signature is obviously not conclusive). For this and subsequent tests, the second processor allows the primary chip set to run a certain length of time and then it resets the chip set and begins again. This is very convenient for finding timing irregularities. Also, the 8048 brings up only one additional chip at a time to permit unambiguous diagnostics.

At some point, signature analysis testing requires the CPU to provide its own stimulus. This is accomplished by inserting a special option ROM. Executing from this, the CPU exercises its own RAM, ROM, and peripheral chips while providing a signature analysis window by using an uncommitted translator chip output.

Because of the heavy dependence on the second processor for service mode, the question logically arises, "What if the 8048 fails?" This is not a problem for several reasons:

1. Assuming equal chip reliabilities, the 8048 is much more reliable than the primary chip set just because of the quantity of chips involved. Thus, only a small percentage of failures involve the 8048.
2. The primary chip set, because it is distributed over the board, is much more susceptible to process problems (solder shorts, electrostatic discharge, et cetera). The 8048, being only a single chip, is far less susceptible to damage; in fact, it can execute its service mode even with its entire 8-bit data bus shorted to ground.
3. At power-on, the 8048 performs an internal self-test and then exercises one of its I/O pins appropriately. Thus, it is readily apparent if it is bad. If so, a bad 8048 is quickly replaced.

Whether or not the 9915A internal interface is present indicates which model computer the Program Development ROM is in, an HP-85 or a 9915A. If the internal interface should fail, the 9915A will wake up and act like an HP-85.

The block diagram in Fig. 2 shows how the HP-85 architecture is partitioned in the 9915A. The keyboard-controller chip is used in the 9915A for the front-panel function keys and interval timers. Buffering for the full remote keyboard is provided in the Option 002 Operator Interface, which also provides additional buffering and the read/write memory for the display. The CRT controller chip is also used in the 9915A because the system uses the CRT retrace signal for various timing purposes. The printer controller chip is included in Option 002 because it contains the character ROM for alphanumeric labeling of the graphics screen. The tape controller chip is used in the Option 001 Tape Drive.

Operator Interface

User requirements for automation controllers diverge widely when it comes to definition of the operator interface. While the programmer has a well-defined set of requirements—keyboard, CRT, printer, and mass storage—no such common requirement emerges when controller applications are examined. Automating incoming inspection might require a full keyboard and printer to document results adequately. A large coordinate measurement machine, on the other hand, might require several large eight-digit displays, a joystick, and a few pushbuttons. A facilities management controller might require a large panel of pushbuttons, one per function, and numerous status indicator lights, while a simple production test setup might not need any interface at all, other than to its test instruments.

The standard front panel of the 9915A (see Fig. 1) is designed to meet the needs of as many minimal-front-panel users as possible. Conspicuous by their absence are typical computer control functions like HALT, RUN, and RESET. In their place are just two system control keys—**AUTO START** and **SELF TEST**—and three system status indicators—**POWER ON**, **SELF TEST**, and **RUN** (BASIC). Controls like RESET, PAUSE, CONTINUE, and RUN are primarily used in system debugging and are rarely if ever required during normal operation.

The two controls that are provided take care of virtually all the needs of the system operator (a third control, the power switch, is on the back and should handle any remaining conditions). Basically, there is one front-panel key (**AUTO START**) to get the machine to a known state and the second (**SELF TEST**) to determine if the machine needs service. Either key, unless explicitly disabled by the user program, will halt the 9915A regardless of what it is doing and return the hardware to its power-up state.

The **AUTO START** key begins the normal power-on sequence of initializing the system, performing a cursory self-test of the machine, loading the Autost program from EPROM or tape (if Option 001 is installed), and running the program. The **SELF TEST** key begins the same sequence, but after completion of power-on initialization it causes an extensive self-test to be performed. The **SELF TEST** key also serves as a lamp test key by turning on all front-panel LEDs (except the activity light for the optional tape drive) whenever it is held down. Both keys are interlocked with the blue shift key to reduce the danger of accidental activation.

The three status lights were chosen to represent those conditions most informative to the operator. The **ON** LED indicates that the 9915A power supply is producing +5V. The **RUN** LED says a BASIC applications program is controlling the 9915A's actions and the system can respond to the front-panel special-function keys or other operator interface. If the **RUN** light is off, the applications program requires operator intervention. Typically the program is either waiting on an input statement or halted due to an untrapped error, but in any case is no longer in control of the system. The third system LED, the **SELF TEST** light, provides pass/fail status of the last self-test performed, be it the one automatically executed as part of power-up or **AUTO START**, or the extensive confidence test initiated by the **SELF TEST** key. This LED will glow any time either style of self-test is initiated and will go out only if no errors are detected.

Above the system control and status area on the front panel is the program-defined interaction area. There are four special-function keys plus a shift key because the HP-85 has four shiftable special-function keys. There are eight annunciator LEDs to provide one pair of LEDs for each special-function key. The label area between the special-function keys and the LEDs holds a replaceable plastic insert which may be printed or silkscreened as desired to show the applications defined for the keys and LEDs.

(continued on page 31)

Operator Interface Design

by Robert A. Gilbert

Flexibility is the key attribute of the 9915A's operator interface card (OIC). Because many applications require more interface capability than provided by a simple front panel, the controlling computer must have a hardware and software interface that is able to accommodate a variety of circuits and peripherals. Terminals and printers can be connected with existing I/O cards (HP-IB, RS-232-C, and GPIO), so the major emphasis is to provide a flexible way to connect keyboards and video displays (Fig. 1). To do this the OIC has three connectors on the rear panel:

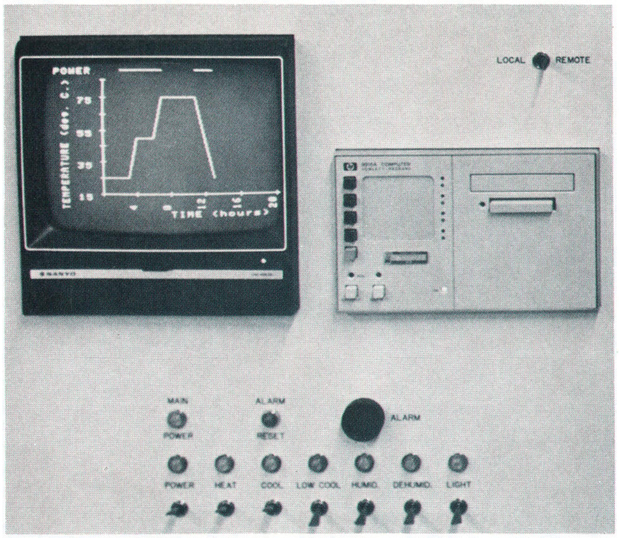


Fig. 1. *The operator interface card simplifies the task for a system designer who wants to connect a custom keyboard and video display to the 9915A.*

1. Keyboard connector. Provides buffered row and column scan lines and programmable speaker output.
2. Control connector. Provides buffered signals that are parallels of the front-panel lights and keys.
3. Video connector. Provides composite video for an external raster-scan monitor.

System integration is sometimes a difficult and costly part of completing a system, particularly if the operator interface for system feedback requires a custom design. To minimize problems in interfacing to the 9915A, the OIC design was influenced by the following goals:

- The 9915A should be able to use a remote operator keyboard and display at distances greater than 10 metres.
- The interface outputs and inputs should be protected from electrostatic discharge damage and shorts to ground or other pins.
- The 9915A should provide composite video for commercially available external raster-scan monitors.
- Circuitry required by the user to interface the OIC to the user's system should be minimal.
- Operator interface card circuitry to which the user must interface should be simple and easy to model and understand.
- Interconnecting cables should not cause RFI/EMI problems.

Keyboard Interface

A custom integrated circuit keyboard/timer controller (KBTC) designed for the HP-85 is used in the 9915A. The KBTC resides on the microcomputer board because the operating system makes use of the four timers in the chip. Designed to interface directly with passive switch keyboards, the KBTC requires buffering of all scan lines to remote the keyboard. A matrix of 10 rows and 8 columns is scanned with each key representing a separate row/column pair. The keys can be used exactly as defined by the operating system (i.e., regular full ASCII keyboard), or by using some of the enhanced BASIC commands provided in the 9915A, every key can be under program control.

The hardware works as follows (see Fig. 2): scanning begins with row R0 and continues consecutively through R9. During each row scan, columns C0 through C7 are scanned with a total scan time of 26 μs for each row/column pair. For the first 13 μs the row and column lines are precharged high (+6V). During the second half of the scan the row line is pulled low (GND) and the column line is monitored to see if it also goes low, indicating that a particular key is pressed.

The row drivers are open-collector buffers. The signals R0 through R9 are pulled up to +5V with resistors to insure that the buffers will indeed see an input voltage that is compatible with TTL gates. The outputs of the buffers are connected to a series resistor that slows down the rise time of the buffer output in conjunction with the capacitor. Each output has a capacitor to ground and

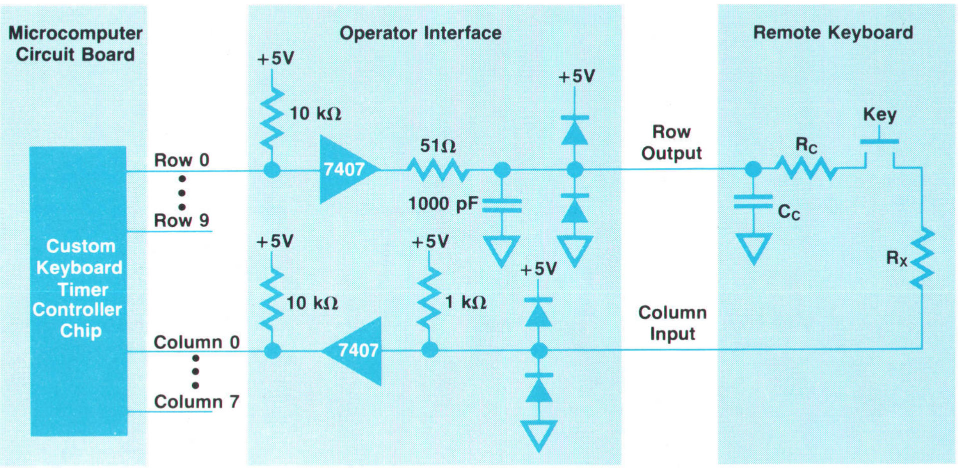


Fig. 2. *Simplified schematic of one row and one column circuit for connecting a remote keyboard to the 9915A using the operator interface card option and the internal keyboard/timer controller chip (KBTC).*

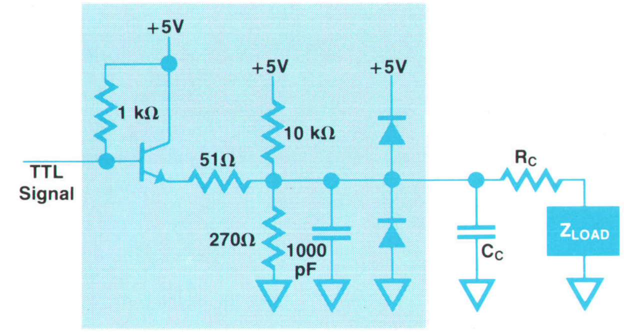


Fig. 3. *Control output buffer circuit in the operator interface card.*

clamping diodes for electrostatic discharge protection. The buffers are open-collector but the pullup resistor is provided by the column receiver circuit. This means that the row outputs float unless a switch between a row and a column line is closed.

The column receivers are also open-collector buffers. The inputs have clamping diodes for electrostatic discharge protection and a pullup resistor that guarantees a high-level input when a key is not pressed and serves as a pullup resistor for the row driver when a key is pressed. The output of the buffer is connected to the operator interface connector and is pulled up to +5V with a resistor to insure that the KBTC sees a high level for its column inputs when the column receiver is not pulled low. Cable capacitance should be kept low by the user so that the RC time constant of the row/key/column circuit is much less than the row/column pair scan time.

Hardware debounce for some keys is not enough and double entries could occur. The operating system is enhanced to do software debounce and eliminate double entry problems. The first time a key is pressed the hardware generates an interrupt and the keyboard handler accepts the key code. If the keyboard handler is again interrupted by the KBTC the software looks to see if a different key is pressed, and if not, waits about 50 ms to check again. In this way double entry is prevented while still allowing rollover if a key is held down. For sensitive applications the BASIC software can be written to request confirmation of keystrokes.

Control Signal Interface

The control signal interface section buffers the front-panel LED signals, **RUN** light, **AUTO START** key, and **SELF TEST** key. Another signal allows detection of a 9915A reset condition.

The LED signals, **RUN** light, and the **SELF TEST** light all use the same buffer circuit (see Fig. 3). The input signals to the buffers are pulled up to +5V with a 1-kΩ resistor. The resistor is connected to the base of a transistor connected in a voltage follower configuration. The output voltage of the transistor emitter should be between 3.6V and 3.2V depending on the gain of the transistor (typical is 3.5V). The emitter voltage is divided to produce an output voltage that is connected to the respective output pin. Clamping diodes are used to provide electrostatic discharge protection and capacitors are used to decrease RFI. The 10-kΩ resistor insures that the output voltage for a low-level input is also low, since for a low-level input the transistor turns off.

The input buffers are open-collector buffers identical to the keyboard column receivers in Fig. 2.

Video Interface

The video interface provides for connection of external CRT monitors and its video section supports a composite video signal similar to RS-170 requirements. The video interface section (Fig. 4) consists of four sections; CRT RAM (random-access memory), a custom IC that generates characters for graphics, a digital sync generator, and an analog composite video generator.

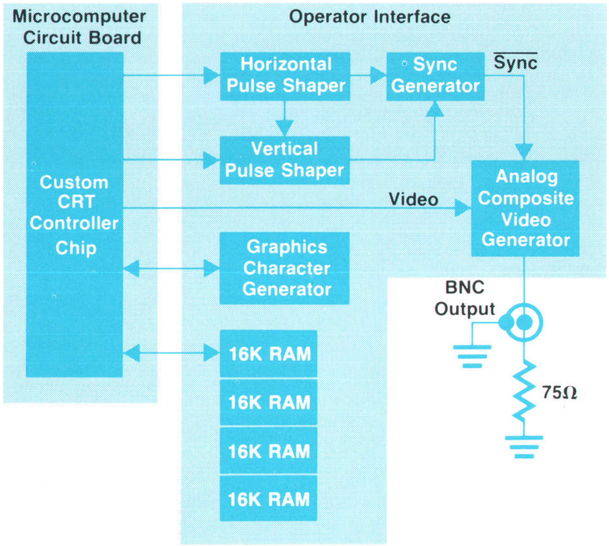


Fig. 4. *Block diagram for video interface portion of operator interface card.*

The CRT controller chip (CRTC) resides on the microcomputer printed circuit board because the operating system requires the CRTC to be present (i.e., the software checks CRTC status registers at various places). The CRTC interfaces directly to four 16K dynamic RAMs and provides fixed horizontal and vertical timing pulses. Because the pulse timing is not programmable and the pulse widths do not match those needed by the RS-170 video interfacing standard, the horizontal and vertical timing signals are shaped. These signals are processed by a digital state machine to form a combined digital sync signal. Video and the sync signal are then combined in an analog circuit to form a composite video signal.

Robert A. Gilbert

Bob Gilbert was originally from Galveston, Texas and attended the University of Texas at Austin, earning a BSEE degree in 1975 and a MSE degree in electrical engineering in 1977. He came to HP in that same year as an R&D engineer at the Desktop Computer Division. Bob was the hardware designer for the 9915A. He is a member of the Institute for Environmental Sciences and has authored two papers on data acquisition/control and reliability strife testing. Bob is married, has one son, and lives in Loveland, Colorado. Bob plays intramural basketball and softball at HP and enjoys water skiing, contemporary Christian music, and electronics.

Extended Operator Interface

In many applications, the eight special-function keys and LEDs provide all the operator interfacing required. In applications where they are superfluous, they represent a minimal burden because they have no effect unless explicitly enabled by the current program. In applications where this minimal interface is insufficient, the optional operator interface card, Option 002, is available (see page 29).

Environmental Considerations

After operator interface flexibility, probably the most crucial need is product survivability. While the desktop computer is pampered by virtue of being normally kept in an office or laboratory area (nobody wants to work at a desk in temperatures over 40° C), the automation controller often must work in a fully loaded relay rack on the job site. Nor are the evils of rack mounting limited to temperature extremes. Equally important are electromagnetic compatibility and tolerance for shock and vibration. Also, fault isolation without having to dismount the box from the rack can save hours of troubleshooting time.

The outside appearance of the 9915A provides the first clue to its approach to survival. Except for the front rack-mount casting and molded plastic front panel, the entire case is sheet metal. The top surface is one unbroken sheet to provide protection against spills and falling objects. The metal case and conductively coated front panel also enhance its electromagnetic compatibility, both as a transmit-

Cost-Effective Industrial Packaging

by Eric L. Clarke

At first glance, the 9915A appears to be another of HP's standard instrument packages, but in fact the package is a two-piece case that is aesthetically compatible with HP's System II cabinet line. This concept in product design evolved from a rigorous set of design criteria that includes operation in an industrial environment and manufacturability on a high-volume basis.

The 9915A is an industrial instrument controller, which requires that the product meet or exceed HP's industrial application specifications. These include shock and vibration testing, temperature testing, electromagnetic emission and susceptibility limits, and humidity/condensation testing.

An extensive thermal study was initiated early in the design phase. This study showed that there were two temperature-sensitive areas in the 9915A: the custom LSI chip set and the optional magnetic tape system. The chip set is specified for a maximum temperature of 65°C, allowing only a 10°C temperature rise above the required maximum operational level of 55°C. This places the product between the capabilities offered by a pure convective cooling system and a forced-air system. The forced-air system was selected on the basis of additional reliability because of lower component operation temperatures.

Conventional forced air systems distribute cooling air throughout the package using an air plenum and ducting arrangement. This channeling of the air flow can add significant cost to the package. In the 9915A a different approach was used for air distribution. Cooling air enters through a perforated area distributed over the entire bottom of the package. This distributed intake acts as a simplified plenum. The incoming air is channeled by the main printed circuit board, which is horizontal with one edge against the fan side of the box. Air flows in from beneath the board and around the free edge. The air then flows across the width of the board, through critical areas, and exhausts through the fan. Holes were left in the printed circuit board around temperature-sensitive components such as the LSI chip set and high-power dissipating areas in the power supply to allow extra cool air to flow over these components. The intake areas near the front of the 9915A and on the front panel were opened up to allow extra air flow around the tape unit. This allows tape operation up to limits inherent in the media and extends tape life.

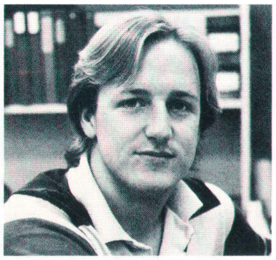
This approach eliminates the need for expensive air distribution systems without sacrificing cooling system effectiveness. In the finished product, maximum internal temperature rise is limited to 5°C above ambient. This system also eliminates the need for an air filter and associated filter maintenance. Because it is a low-volume air system with a large intake area, the incoming air velocities are very small. This, coupled with the incoming air traveling upward, acts as a natural filter against the air suspension and transport of particles into the package.

During shock and vibration testing in the early design phase there were two major objectives. The first objective was to establish the structural integrity of the box in an abusive environment. The second was to locate and eliminate problems leading to field turn-on failures due to shipping and handling damage. A process of shaking, breaking, analyzing failure modes and design optimization was used to attain these goals. From these tests, a stronger rivet material was selected, printed circuit boards were mounted more securely in their edge connectors, and the structural rigidity of the tape system was improved.

A sheet metal chassis is the base of the unit. One side of the chassis is for mounting the primary electrical parts and the fan. The opposite side is open to permit accessibility. The main printed circuit board snaps into place in the chassis and power is connected through a removable plug. The subassemblies connect to the main board through right-angle edge connectors and are secured with a minimum number of fasteners. The package is covered by a one-piece slide-on cover. The mechanical assembly of the 9915A takes less than 30 minutes. For service, any of the printed circuit boards can be removed from the unit within five minutes.

Acknowledgments

The author thanks Hugh Flemming for his time in the design area and thermal study of the 9915A, the Environmental Test Group for their time and inputs, and Don Faatz for his technical assistance on plastic parts.



Eric L. Clarke

Eric Clarke came to HP in 1979 after receiving the BSME degree from California Polytechnic State University. He started work on the 9915A and now is involved with modular computers. Eric was born in Waltham, Massachusetts and lives in Fort Collins, Colorado. During his leisure time he enjoys skiing, rafting, and volleyball.

ter and as a receiver. German VDE (Verband Deutsches Electrotechniker), U.S. FCC (Federal Communications Commission), and CISPR (International Special Committee on Radio Interference) requirements for radiated and conducted interference are all easily met with wide margins.

Full industrial temperature range operation requires more than the packaging design discussed in the box on page 31. While the HP-85 system offers cartridge tape and several flexible-disc mass storage options, none is recommended for operation at 55°C. The 9915A solves this problem by using an EPROM. However, instead of the traditional approach which uses an EPROM directly as computer instruction memory, our approach was to access the EPROM indirectly. When a program is to be run from the EPROM, it is downloaded to system memory and executed there. While this introduces a program load delay, it allows far better use of EPROM storage space. On the 9915A, which dynamically allocates memory between program code and variable storage, the added flexibility is essential.

This approach also allows simple implementation of remote storage. EPROM access commands can be directed to an I/O interface card instead of the EPROM. Either of two simple protocols can be used to load programs into a 9915A (or an HP-85 with program development and I/O ROMs) through an I/O interface. In a limited networking application, this allows a central computer, situated in a more benign environment, to download programs on request to units on the factory floor.

Acknowledgments

The design of the first entry into a new product area can be successful only if supported by all concerned. The 9915A is not an exception, and many people made critical contributions to the project. The formal product design team members, in order of appearance on the project, were Jerry Nelson, lab manager, Dick Barney, Section Manager, Ken Watts, project manager, Bob Gilbert, main processor and operator interface, Jim Brokish, power supply, Eric Clarke, packaging, Hugh Flemming, cooling, Dave Sweetser, self-test and tape transport, Tom Moy, reliability, Mark Davis, production test, Bruce Young, software Q/A and strife testing, and Carl Anderson, production test.

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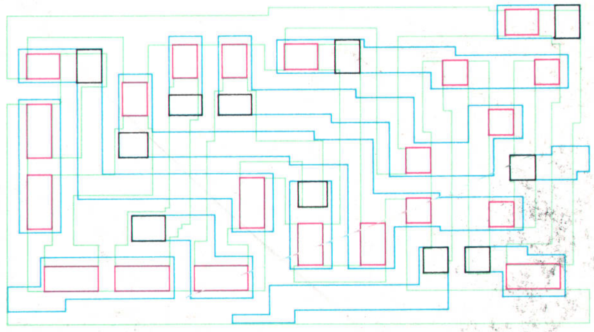
Vincent C. Jones

Vince Jones joined HP in 1979 and has been involved with the design of the 9915A and its enhancements. Before joining HP he worked on computer network access and remote sensing systems and did occasional consulting for small business computer users. Vince served four years in the U.S. Air Force, attaining the rank of Captain. He is a graduate of Rutgers University, New Jersey (BA and BS degrees, 1970), and received the MS and PhD degrees in electrical engineering from the University of Illinois in 1972 and 1975. He is a member of the IEEE and has written five papers on the use of microcomputers and man-machine interfacing. Vince is a native of New Jersey, married, and has three daughters. He and his family enjoy living in Fort Collins in the shadow of the Colorado Rocky Mountains.

CORRECTION

In the June issue, Fig. 2a on page 26 was printed incorrectly. Here is the correct version.



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JULY 1981 Volume 32 • Number 7

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