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10780A RECEIVER

Laser Transducer Systems for High-Accuracy Machine Positioning

These reliable, modular systems consist of an HP two-frequency laser head and interferometric optics designed for permanent installation on a machine tool or measuring machine, and a selection of interface electronics to couple the laser to a computer, calculator, or numerical controller.

by André F. Rudé and Michael J. Ward

SHARPENING THE EDGE OF PRODUCTIVITY is the endless task of the manufacturing industry. Today, the principal means to this end are flexible, technology-rich machines, designed to operate reliably on a continuous basis, automatically monitoring and adjusting themselves.

Accurate position determination is essential to such machines. Constantly striving for more accuracy, many builders and users of machine tools are now using laser interferometers as position transducers, permanently installed on their machines. Computer disc drive manufacturers are beginning to do likewise. A pioneer in the use of laser position feedback is the integrated circuit equipment industry, which has used laser interferometers for many years in step-and-repeat cameras, IC mask generators, and mask measuring machines.
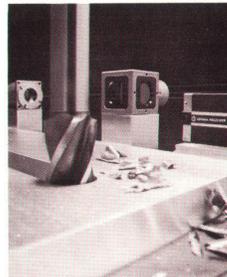
Hewlett-Packard's Model 5501A Laser Transducer is designed for this type of service. As the basis of a linear displacement measuring system, the laser transducer delivers the advantages of interferometry at a cost comparable to that of conventional devices. With a single laser source, up to six axes of motion may be monitored. A new remote receiver eliminates the need to return the laser beam to the laser source. An expanded choice of output electronics provides for feedback control by computers, calculators, or other controllers, or for digital display, or both. Although the laser transducer is designed for original equipment manufacturers, simple installation techniques make it suitable for retrofit by end users as well.

Advantages of the Laser Transducer

The laser transducer offers several advantages over conventional position transducers, including inductive scales, linear encoders, and linear-to-rotary motion encoders such as rack and pinion, roller on a way, or metallic tape on a drum.

Accurate within 0.5 part per million, the laser is a linear standard, bringing to the factory a degree of accuracy that formerly could be obtained only in the standards laboratory. It permits positioning of machine tool elements by numerical control at least an order of magnitude more accurately than other transducers. New and old machines alike can benefit, but the improvement factor may be even greater on an old machine with a worn lead screw. Periodic calibration is not needed; the laser retains its accuracy because its wavelength is locked to an atomic transition in neon and to the velocity of light.

Cover: *Our art director creates a sculptural representation of the 5501A Laser Transducer System for machine-tool positioning. His raw materials are a machined part and some chips, a cutting tool, laser light, and three of the rugged, miniature Laser Transducer modules designed for installation on a machine.*

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Another advantage of the laser is good linearity— better than 0.5×10^{-7}, much better than metallic tape, a linear scale, or a precision lead screw. Resolution is also superior. The basic resolution of 0.16 micrometre can be extended electronically to 0.016 micrometre.

The laser transducer is not limited to linear measurements. Using available optical options, it can monitor straightness, yaw, pitch, or other parameters of machine geometry. Long travel—up to 60 metres (total of all axes)—can be handled.

The laser transducer is easy to install and easier to align than glass or inductive scales or lead screws. Little maintenance is required because the laser and optics are not subject to wear. Reliability and serviceability are enhanced by diagnostic circuits built into the system electronics.

Remote interferometric design makes it possible to keep the laser source, which generates a small amount of heat, well away from the axes of motion and other thermally sensitive areas. A wide selection of optical components provides the versatility needed for optimum configuration of a new machine or easy retrofit of an old one.

The main disadvantage of the laser transducer is that, like inductive scales, it requires considerable electronics and signal conditioning. Also, to obtain maximum accuracy it is necessary to compensate for very slight changes in the wavelength of the laser light caused by changes in the index of refraction of air because of variations in temperature, pressure, and humidity. Compensation is an added cost. However, the compensator can also be used to apply scale factors and reduce known systematic errors.

Configuring a Laser Transducer System

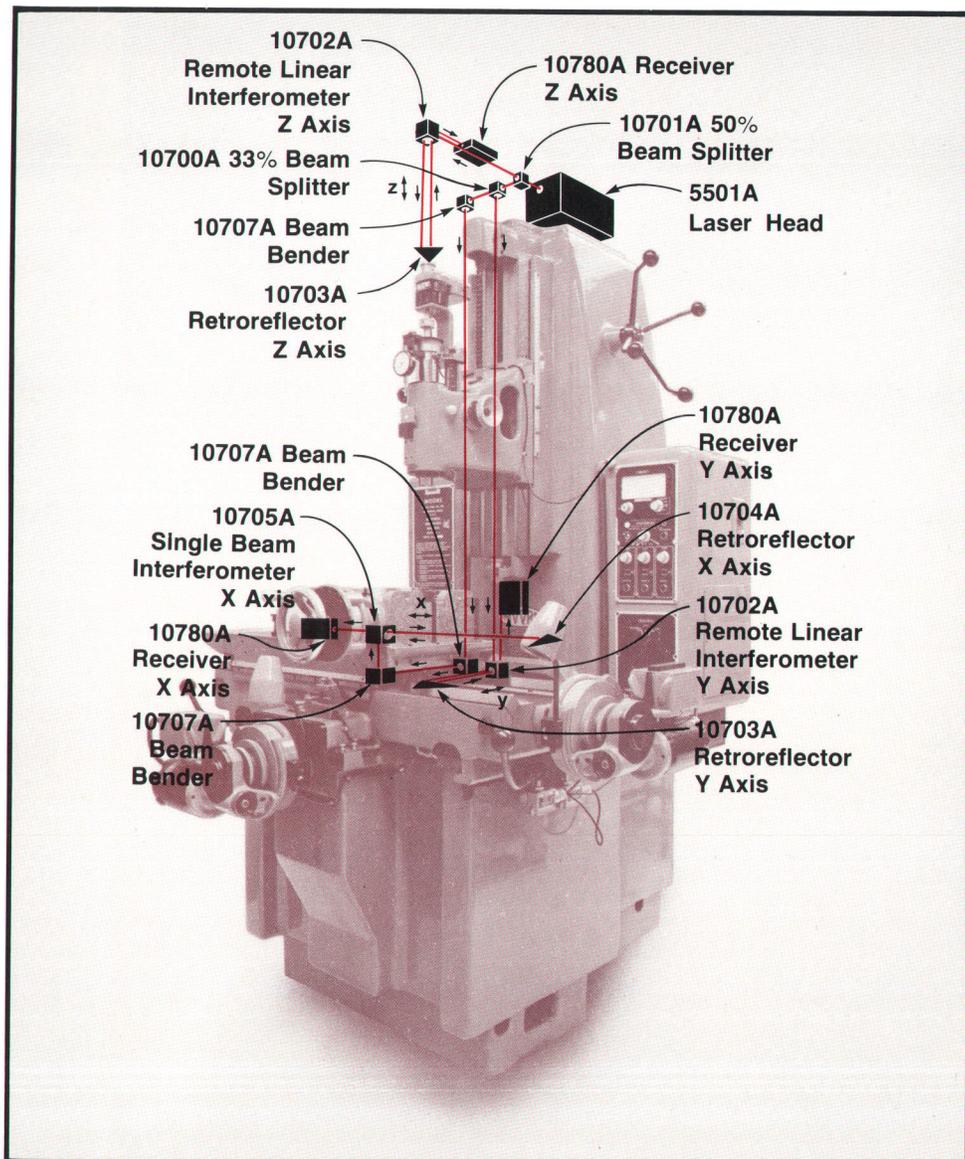The configuration of an HP laser transducer system

Fig. 1. *A typical Model 5501A Laser Transducer System installed on a three-axis coordinate measuring machine. A single laser source serves all three axes.*

3

is different for different machines. However, all configurations require five choices:

- A two-frequency laser source and associated circuits
- Accessories for each axis of measurement (up to six axes)
- Optics to direct the laser beam to the measurement axes
- Output electronic format and options
- Cables and power supplies.

Fig. 1 shows a typical installation on a measuring machine.

The Laser Head

The source of the laser light for the 5501A Laser Transducer System is a laser head that uses the same laser tube as the HP 5526A Laser Measurement System.[1-4] Fig. 2 is the laser head block diagram. The laser package has been redesigned to reduce its cost and make it more convenient for OEM applications, and it now meets NEMA-12 standards for industrial packages.

The laser tube has the advantages of very long lifetime, instant-on service, and automatic tuning. It is a two-frequency laser source; that is, the laser beam contains two components at slightly different frequencies, polarized at right angles to each other. The frequency split is about 2×10^6 Hz, compared to the laser frequency of some 10^{14} Hz, and is produced by an axial magnetic field which causes Zeeman splitting in the energy levels of the laser medium (helium-neon gas).[1]

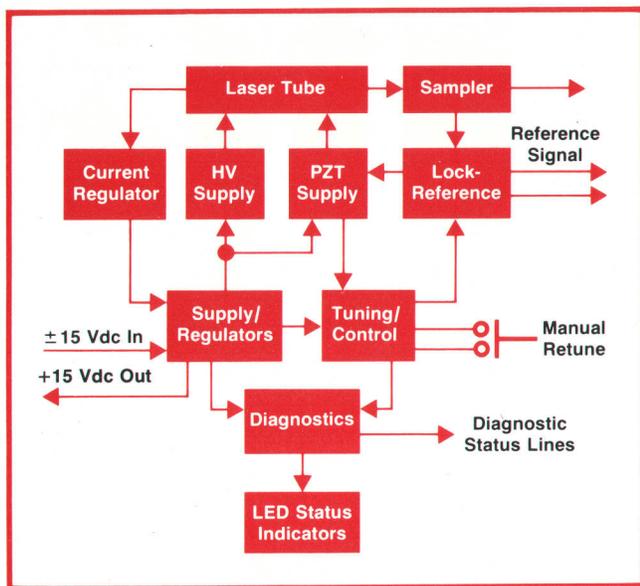The laser system measures displacements by looking at the Doppler shift induced by the motion of the displacements. Both frequencies of laser light come from the laser head to the interferometer, where they are separated optically. One of the two frequency components is directed to the object whose motion is being measured. There it is reflected by a mirror or retroreflector (cube-corner) and returned to the interferometer. The effect of the motion is to cause a Doppler shift in the frequency of the reflected component. The two laser light components now differ in frequency by the original frequency split plus or minus the Doppler frequency shift. By integrating the total positive and negative excursions in the difference frequency, the system can find the net displacement in wavelengths of laser light.

The primary advantage of the two-frequency "ac" measurement system is its much greater usable dynamic range, compared to older, single-frequency "dc" laser interferometer systems. For example, in the laser transducer system, the nominal output power is 120 microwatts, but the power returned to the laser receiver can be as low as four microwatts and the laser will continue to operate the system. The 5501A Laser Transducer system takes advantage of this wide dynamic range by moving the receiver from inside the laser head, where space considerations would limit the number of receivers, to the outside world. As a result, a single laser head can drive up to six linear measurement axes; this can cut the cost per axis significantly. Furthermore, the remote receivers can be mounted wherever most convenient; the laser light need not be returned to the laser head.

The laser head provides TTL-logic-level diagnostic signals that indicate the status of its auto-tune circuit and supply voltages to the system controller. Eight rear-panel light-emitting diodes give the same information in visible form. A RETUNE pushbutton provides for manual tuning whenever the laser exceeds its auto-tune range. The same function can also be commanded by an external controller.

Measurement-Axis Accessories

Three accessories are required on each measurement axis: an interferometer, a retroreflector or mirror, and a 10780A Receiver.

Three types of interferometers and reflectors are available. The standard combination is the 10702A Linear Interferometer with the 10703A Retroreflector. When space for optics and beam paths is limited, the 10705A Single-Beam Interferometer may be advantageous; its reflector can be either a flat reflective surface or the 10704A Retroreflector. Twice the resolution of these interferometers is provided by the 10706A Plane-Mirror Interferometer; it is designed to be used with a high-quality plane mirror reflector.

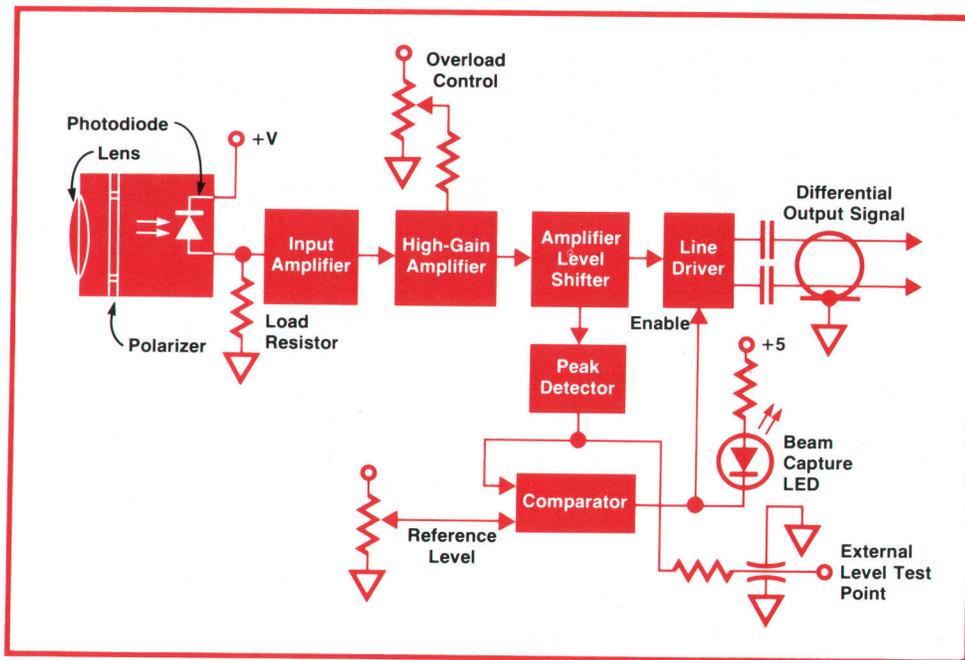The 10780A Receiver converts the Doppler-shifted

Fig. 2. *The laser source has the same long-lifetime, instant-on, two-frequency laser tube that has been used for many years in HP's Laser Measurement System.*

4

Fig. 3. *10780A Receivers, one for each measurement axis, convert the received laser light to electrical signals. Laser head and receiver enclosures meet NEMA-12 standards for industrial packages.*

laser light into electrical signals that can be processed by the rest of the laser system. The receiver contains a photodetector, an amplifier and level translator, a line driver, a level sensor, and local voltage regulators. Fig. 3 is its block diagram.

A lens on the front end of the receiver focuses the laser light onto the active chip of a silicon PIN photodiode. Between the lens and the diode is a small piece of polarizing material oriented at 45 degrees to the horizontal and vertical axes of the receiver. When the receiver is mounted properly—vertical axis parallel or perpendicular to the axes of the laser head—the polarizer passes one-half the incident power from each of the two incoming orthogonally polarized components of the received laser beam. The resulting power on the photodiode chip is an amplitude-modulated sine wave; its frequency is the Doppler-shifted split frequency, and its amplitude is proportional to the product of the incident powers of the two orthogonal components. The photodiode generates an ac current, which is converted to an ac voltage at a frequency of 100 kHz to 5 MHz.

The detected signal voltage goes through a stage of impedance transformation, two stages of voltage gain, and a stage of level translation. The result, a TTL-level signal, goes to a TTL differential line driver, which is ac-coupled to the rest of the 5501A system by a shielded twisted-pair cable. The output of the line driver is a differential square wave at the Doppler-shifted split frequency.

The level sensor disables the line driver unless the incident laser power is four microwatts or more.

The receiver enclosure is designed to meet NEMA-12 standards for industrial packages. The receiver is mounted by its two aluminum end caps, which are tapped for machine screws. Four plastic spacers (part of the end caps) separate the receiver case from its mounting plate and allow full air circulation around the receiver to carry away the heat it generates (nominally two watts). By using Nylon mounting screws, the entire receiver can be electrically isolated from its mounting plate; this allows ground loops to be broken, which can be important when there are large electrical transients in the dc power lines or large ac ground currents running through a machine.

Beam-Directing Optics

The 10707A Beam Bender and the 10700A and 10701A 33% and 50% Beam Splitters are designed to "pipe" a portion of the laser beam to each measurement axis. To avoid beam attenuation, the beam splitters must be oriented so the reflected beam forms a right angle with the transmitted beam and the two beams are coplanar with one of the polarization vectors of the input beam. Other considerations, and the method of calculating path loss to make certain that each axis has sufficient beam power, are given in the Appendix.

Output Formats

Many different output formats are available to adapt the laser transducer system to specific applications. Detailed information on all the output electronics options for the 5501A laser Transducer is presented in the article beginning on page 7.

Acknowledgments

The 5501A Laser Transducer system has had many contributors. Fred London, our marketing manager,

5

assisted by Duncan MacVicar and George Carey, and Jim Koch, our engineering section manager, were constant contributors to the definition of the product. Dick Baldwin provided technical expertise in the field of optics. Dave Ricci, Steve Schultz, and Allen Foster gave us valuable information on the HP Interface Bus. Chuck Lowe handled the product design for the laser source and the 10783A display with help from Rick Austin. Credit should also be given to two earlier contributors, T.C. Teng and Barbara Grote.

Mike Freeman coordinated manufacturing tooling. Roy Criswell, Len Kraska, Randy Sharp, Larry Ligon, John Schmitz, Bob Boss, and Mike Petretto handled the smooth introduction into production. Technical support to customers and field engineers is provided by our applications engineer, Steve Cline. ⌂

References
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2. R.R. Baldwin, G.B. Gordon, and A.F. Rude', "Remote Laser Interferometry," Hewlett-Packard Journal, December 1971.
3. R.R. Baldwin, B.E. Grote, and D.A. Harland, "A Laser Interferometer that Measures Straightness of Travel," Hewlett-Packard Journal, January 1974.
4. G.O. Herreman, "Laser/Calculator System Improves Encoder Plate Measurements," Hewlett-Packard Journal, June 1973.

APPENDIX

Some Things to Keep in Mind When Configuring a Laser System

Multi-axis systems must be designed with sufficient safety margin in the power received by the 10780A Receiver. Computation of beam path loss is straightforward (see example). The minumum output power of the laser head is 120 microwatts; most exceed this figure. Each laser is measured for output at the factory. The output power is relatively constant over the usable life of the tube and tends to drop off slightly toward the end. The minimum necessary power at the receiver is four microwatts. For a three-axis system, then, the power safety margin would be 40 μW ÷ 4 μW or 10:1.

Things are not quite so simple in the real world, however. 33% beam-splitters are not actually 33% but more on the order of 33% ±5%. Beam-benders with dielectric coatings can reflect 99% of the light; these are the kind HP provides. Some beam-benders are only 80-95% reflective, and using more than one causes the losses to multiply. Cube-corners are typically 80% to 90% reflective. Dirt on the optics reduces the amount of light at the receiver. Poor alignment of the optics or the receiver reduces the amount of light detected by the receiver photodiode. This specifically includes misalignment of the optics causing the position of the beam at the receiver to wander as the object being measured runs down its travel. Fluctuations of the refractive index of air in the path of the interfering beams, which can be caused by local temperature differences, cause the laser beam to lose some of its coherence and may break it for an instant. This will cause an error in the counter part of the system, and will shut the system down. The smaller the received signal safety margin, the more likely the fluctuations will be to break the beam. These fluctuations should not be confused with air flow, which does not affect accuracy and repeatability. In fact it is desirable to have some air circulation to help eliminate gradients in the refractive index of air.

Some of the modules derive their supply voltages from other modules, and the voltage drops in the connecting cables limit the total length of individual cables. The five-volt dc supply for the 10740A Coupler must be remote sensed at the backplane. Other modules have specific maximum cable lengths defined for specific supply voltage ranges as measured at the source ends of the cables.

Calculating Path Loss

One thing that must be kept in mind when calculating the path loss in an axis of the laser beam is that the optics split the two frequency components of the laser beam into two separate paths for each axis and the losses are normally computed separately for each of the two components. Since the laser beam is detected by a mixing process and the result is proportional to the product of the powers of the two frequencies, the loss bookkeeping can be handled by calculating an attenuation factor for the path. The overall attenuation factor is then the product of all the individual attenuation factors.

The minimum power at the receiver must be four microwatts, and the guaranteed minimum power out of the laser is 120 microwatts, so the maximum allowable attenuation factor is $(4/120)^2 = 0.0011$. Some typical attenuation factors for transducer optical modules are as follows (these are worst-case numbers, which must be used for loss computation):

10700A	33% Beam Splitter 33% side	0.08
10700A	33% Beam Splitter 67% side	0.38
10701A	50% Beam Splitter each side	0.19
10702A	Linear Interferometer	1.00
10703A	Retroreflector	0.80
10704A	Retroreflector	0.80
10705A	Single-Beam Interferometer	0.85
10707A	Beam Bender	1.00

As an example, consider a typical installation with three axes. Assume linear interferometers on each axis, good optical alignment, and comparable path lengths (so the *relative* effect of air turbulence may be left out of this quick calculation). Assume that the three axes have the following components:

Axis A: 10700A (33%), 10707A, 10702A, 10703A (2)
    B: 10700A (67%), 10701A, 10702A, 10703A (2)
    C: 10700A (67%), 10701A, 10707A (2), 10702A, 10703A (2).

The attenuation factors are, for each axis:

Axis A: (.08) (1.00) (.80) (.80) = 0.0512
    B: (.38) (.19) (.80) (.80) = 0.0462
    C: (.38) (.19) (1.00) (1.00) (.80) (.80) = 0.0462

Here, B and C are worst case (net product is smallest) but still have an attenuation factor 42 times greater than 0.0011. This is to say, these axes can operate with an additional attenuation factor caused by dirt, misalignment, air turbulence, etc. of up to 1/42 = 0.024.

SPECIFICATIONS
HP Model 5501A Laser Transducer System

RESOLUTION: 6 microinches (0.16 micrometres) or 3 microinches (0.08 micrometres) using plane mirror interferometer
  NOTE: Increased resolution available via resolution extension.

ACCURACY: ±0.5 parts per million.

RANGE: Up to 200 feet (60 metres) depending on conditions (sum of axes for multi-axis configurations).

NUMBER OF AXES: Up to 6 depending on system configuration and environmental conditions.

MAXIMUM ALLOWABLE LASER BEAM LATERAL OFFSET: ±0.2 inch (±5 mm)
  An interferometer or retroreflector may be offset by a maximum of ±0.1 inch (±2.5 mm) since the reflected beam is displaced by twice the retroreflector displacement.

MAXIMUM ALLOWABLE VELOCITY: 720 inches/min (18.3 metres/min) 360 inches/min (9.14 metres/min) using plane mirror interferometer.

ENVIRONMENTAL
  NON-OPERATING: −40°F to +167°F (−40°C to 75°C) 0% to 95% relative humidity.
  OPERATING: 32°F to 130°F (0°C to 55°C) 0% to 95% relative humidity.
  EXTREME TESTS: All system modules have been tested to withstand the following extreme conditions:
    Vibration: 10 to 55 Hz at 0.010 inch (0.25 mm) peak-to-peak excursion on all three orthogonal axes.
    Shock: 30 g for 11 milliseconds.
    Electromagnetic Compatability (EMC): MIL-I-6181D for interference, susceptibility, magnetic conditions.
    Power Excursions: 10 microsecond spikes of 100 volts positioned from 0° to 360° of power line phase.

PRICE IN U.S.A.: Typical 3-axis system, $4000 to $7000 per axis, depending on configuration. OEM discounts available.

MANUFACTURING DIVISION: SANTA CLARA DIVISION
                5301 Stevens Creek Boulevard
                Santa Clara, California 95050 U.S.A.

Electronics for the Laser Transducer

The emphasis is on flexibility and completeness, making the system adaptable to virtually any combination of controller and machine.

by William E. Olson and Robert B. Smith

OUTPUT ELECTRONICS for the 5501A Laser Transducer System are available in a variety of forms. General-purpose interface electronics include a universal binary interface for virtually any digital processor or controller, a calculator interface based on the Hewlett-Packard Interface Bus (HP-IB) and HP programmable calculators, and a universal English/metric pulse output for most numerical controllers. A special low-cost interface for HP 2100 and 21MX Computers, and a very basic quarter-wave pulse output are also available. Other electronic modules provide for manual or automatic velocity-of-light compensation and for the special needs of some closed-loop systems.

Coupler Houses General-Purpose Electronics

Fig. 1 shows all of the presently available general-purpose electronic modules for the laser transducer system. The modular approach allows the user to choose only the building blocks he needs to configure a system to solve his particular problem.

Basic to the understanding of any system that might be built using the blocks shown in Fig. 1 is an understanding of the architecture of the one unit that is always present, the 10740A Coupler. The coupler is an enclosure that functions as a protective housing for the working modules. Electrical interconnection of the modules is furnished by the coupler's printed circuit backplane, which carries the 86-pin connectors into which the modules are inserted. The coupler has no internal power supplies, but supplies power to the modules from external power supplies connected to a barrier strip on its rear panel. Three dc voltages are required: +5V, +15V, and −15V.

Numerical data is transferred between cards over a 28-bit parallel data bus on the coupler backplane. Binary coding is used. A four-bit-wide bus carries decimal point position information, and another four-bit bus carries error flags that indicate the existence of conditions that might make the data invalid. Associated with the data, decimal point, and error flag lines is a status line called Binary Data Valid (BDAV).

Instructions are sent from card to card over an eight-bit-wide instruction bus and two status lines called Instruction Valid (INSV) and Operation Complete (OPC). Instructions consist of two parts: a four-bit alpha address and a four-bit numeric command. Each card in the system has its own hardwired address, fixed in some cases and selectable by means of jumpers or switches in others. The modules and their addresses are:

Module	Address
10745A HP-IB Interface	O
10746A Binary I/O	P
10755A Compensation Interface	V
10760A General-Purpose Counter	X,Y,Z,A,B, or C
10761A Multiplier	M
10762A Comparator	X,Y,Z,A,B, or C
10763A English/Metric Pulse Output	X,Y,Z,A,B, or C

In general, a particular numeric command always has the same meaning. However, different modules respond differently to the same command. An important concept here is that of implied talkers and listeners.

One way to handle communications in a bus-oriented system is to address one module as talker and one or more modules as listeners. This requires two modes of operation, one for addressing and one for data transfer. In a very general system serving as the interface for many different types of units, some of which have not yet been conceived, this very formal organization is mandatory. In the laser trans-
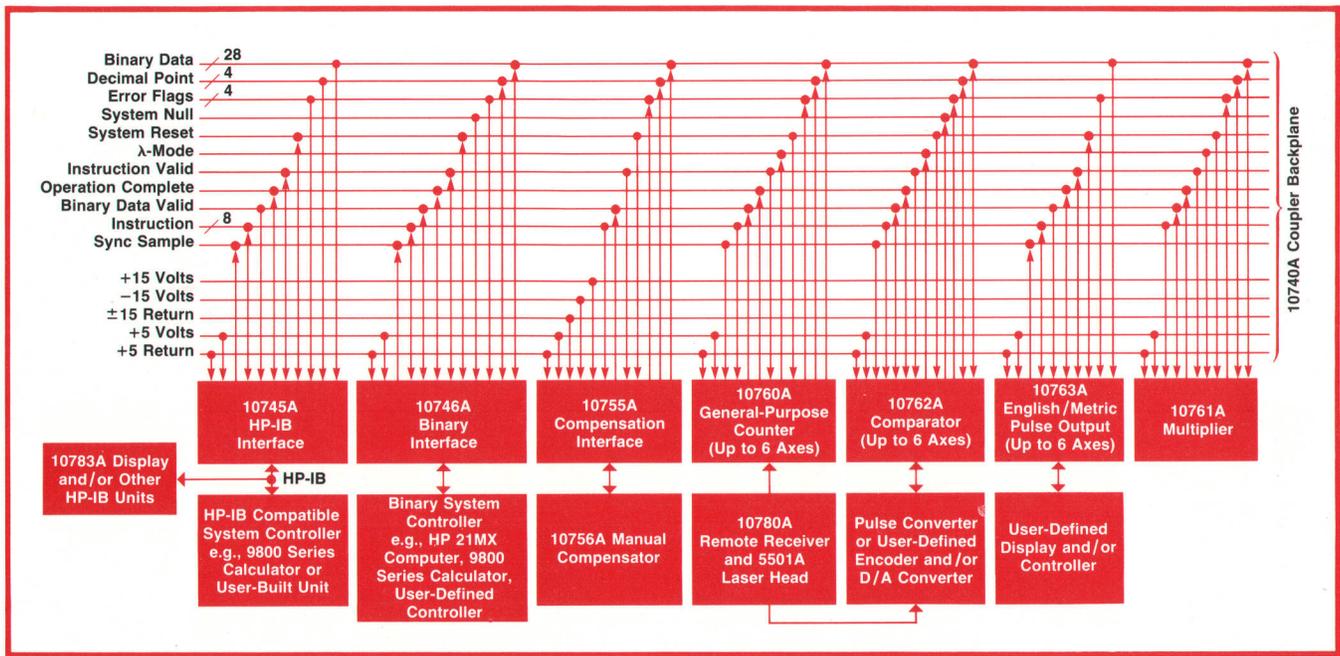
Fig. 1. *Model 10740A Coupler serves as a housing and communications facility for the other electronic modules of the 5501A Laser Transducer System. The user selects the building blocks needed to configure a system to solve his problem.*

ducer system, however, it is possible to make some agreements and speed up the system.

For example, we can make the instruction lines separate from the data lines and agree that all modules will continuously monitor the instruction lines, looking for and reacting to only those instructions that concern them and ignoring those that do not. This means that a particular instruction will have any of several meanings, depending upon a particular card's point of view.

As an example, consider the instruction "2X". The address portion is "X", which could designate an X-axis counter card in the system. From the point of view of the X-axis counter the instruction "2X" means that it should enable its data output buffers, its decimal point position code drivers, and its error flag drivers to the 10740A backplane and set the Binary Data Valid line true. To a 10745A HP-IB Interface card it means load this information into your data register, decimal point code register, and error flag register, and issue a service request, SRQ, if there has been an error. To a 10761A Multiplier, however, it says take the data being output, multiply it by the laser light wavelength corrected for changes in the index of refraction of air, and store the result. The X-axis counter card was the implied talker and the multiplier and I/O card were the implied listeners. It was not necessary to address the counter as a talker or the I/O and multiplier as listeners. This saves time and circuits at the cost of a slight complication in the instruction set for the system.

There are four lines on the 10740A backplane that are dedicated to particular functions and always have the same meaning. Two are nonaddressed commands and two are status lines. System Reset is the command to initialize to some starting condition. This command is generated by the interface modules during power-up; it can also be sent by the system controller. Synchronous Sample is the command to take present displacement information and load it into output buffers. It is used to get a simultaneous sample from all axes. λ-Mode is a status code from counters and comparators, indicating to the multiplier card whether quarter-wave ($\lambda/4$) or eighth-wave ($\lambda/8$) resolution is being used in the system. System Null is a status code from comparators, indicating the system has arrived at the required destination.

General-Purpose Counter

Most systems based on the 10740A Coupler will contain one 10760A Counter card for each measurement axis (the exception is a closed-loop type of system in which the 10762A Comparator card, to be described later, replaces the counter card). The 10760A Counter is a general-purpose counter consisting of line drivers and receivers, a resolution extender, a pulse converter, and a reversible counter (see Fig. 2).

The line receivers accept two differential RF signals, one from the laser source (reference signal), and one from the remote receiver (measurement signal), and convert them to TTL signals. The input signals
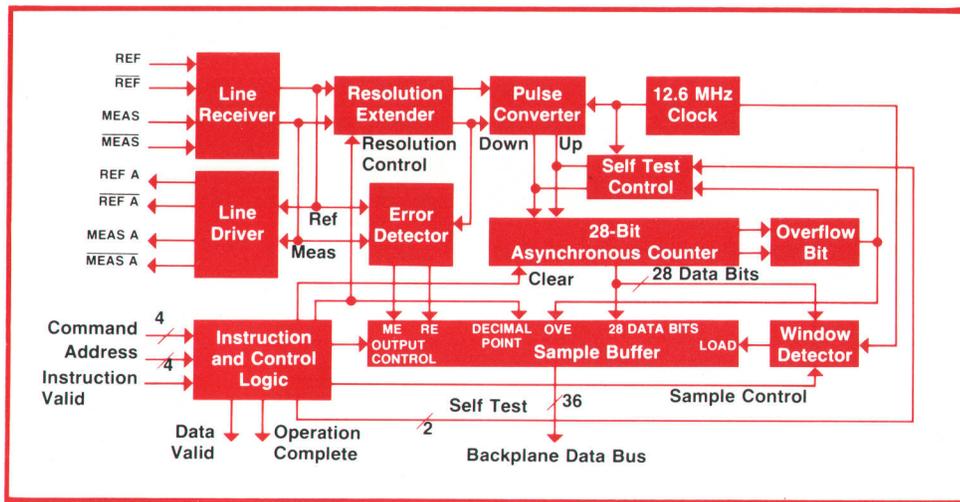
Fig. 2. *Most systems will contain one 10760A General-Purpose Counter card for each measurement axis (up to six).*

are then amplified by the line drivers for use by other cards in the system. For example, the reference signal must be sent to each counter card and must be daisy-chained because the line impedance matching requirement and available line driving power do not allow parallel connection. The measurement signal is also reproduced, and may be used for other signal processing, such as differential measurements using one measurement signal at the measurement input and another measurement signal at the reference input.

The resolution extension circuit allows a user to select normal resolution of 0.16 μm (6 μin) or extended resolution of 0.016 μm (0.6 μin) under program control. The only drawback of the resolution extender is the 1.2-inch-per-second slew rate limitation imposed when resolution extension is in use. This is more than compensated for by the real-time extension in resolution and resulting increase in positioning accuracy.

After the measurement signal has been resolution extended (or not, depending upon program control), the measurement and reference signals are converted to displacement information in the form of up/down pulses, which are fed to a counter. This is done by the pulse converter circuit.

The next functional block on the counter card is a 28-bit binary counter that counts the up/down pulses from the converter to give total displacement information. The delay between a position change on the measurement axis and a change in the counter is on the order of 0.4 microseconds depending on the length of cable between the receiver and the counter card.

In addition to these signal processing blocks, the counter card also has several control and error functions. The error circuits constantly monitor the status of the counter and the conditions of the reference and measurement signals at the input to the pulse converter. If the reference signal is interrupted for more than six microseconds a reference error bit is

set. If the measurement signal is interrupted or becomes invalid because of excessive slew rate, a measurement error bit is set. The error circuits monitor the frequencies of the two signals and set the respective error bit if prescribed limits are exceeded.

The counter status error bit is set whenever the counter chain overflows or underflows. This error is recoverable, that is, it can be corrected by moving the retroreflector in the direction opposite to that which caused the overflow or underflow until the condition is reversed. Thus no counter information is lost. This is not the case for reference or measurement signal errors. Should one of these occur, the measurement axis must be returned to some gage point to redefine the zero point.

The control circuits interpret system instructions and cause the counter to perform the required operation. Test functions are included on the counter card to allow the system controller to check the operation of the counter chain and error bits, the output buffer, and the pulse converter clock.

Binary Multiplier

The 10761A Binary Multiplier card is designed as an optional feature of the laser transducer system. Its main purpose is to perform the conversion of uncompensated fringe (quarter-wave) displacement data from the 10760A Counter cards to either metric units (in millimetres) or English units (in inches) for output to a controller. The multiplier card is not needed if the system controller can perform this conversion rapidly enough by itself.

Fig. 3 is a block diagram of the multiplier card. The input buffer accepts and holds data available from the coupler backplane. This may be velocity-of-light information from a compensation interface card (described later), displacement information from a counter card, or any other applicable backplane data. The next part of the multiplier is a group of AND gates used as data control for the magnitude data stored in
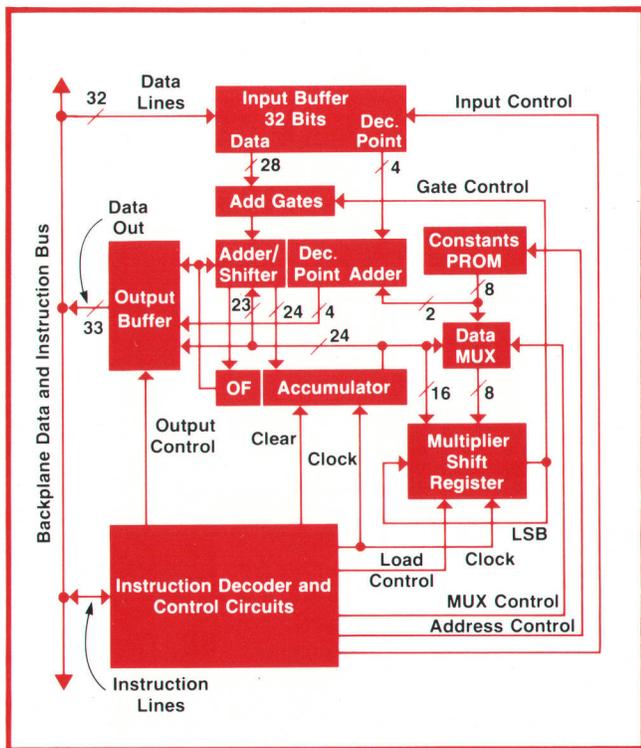
9

Fig. 3. *The 10761A Binary Multiplier is optional. It converts uncompensated fringe (quarter-wave) displacement data from the 10760A Counters to either millimetres or inches. It is not needed if the system controller can perform this conversion fast enough.*

the input buffer. These gates control the add-shift/shift-only function (multiplication is accomplished by repeated shifting and adding). From here the data goes to the adder-shifter section of the card. The inputs to the adder are the outputs of the AND gates and the output of the accumulator. The resulting addition is fed back to the inputs of the accumulator, which is a 29-bit register. The 29th bit is an overflow bit used to indicate that the result of multiplication has a magnitude greater than 28 bits. The multiplier register is a shift register that can be loaded from the accumulator or from a constants ROM (read-only memory) which contains all the conversion constants for the multiplier. This shift register's least significant bit controls the input buffer AND gates.

Besides the main adder there is a four-bit decimal point adder that handles the conversion of the decimal point code for the appropriate measurement units. These circuits are directed by the control logic, which interprets backplane instructions and controls the execution of indicated operations. The control logic has a 10-MHz clock, which allows a complete multiplication in less than five microseconds.

Instructions recognized by the binary multiplier card include reset, English units, metric units, velo-

city-of-light (VOL) output, counter output, and multiplier output. The VOL output instruction is interpreted by the multiplier card as an input operation. The VOL data is loaded into the buffer and then multiplied by the preselected units constant from the constants ROM. The product is stored in the shift register for future use. This result represents a compensated units-conversion number for converting fringe displacement data from the counter cards to the

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A Numeric Display Module

The 10783A Numeric Display provides the laser transducer system with digital display of single or multiple-axis displacement data. It is driven from the Hewlett-Packard Interface Bus in either the "Listen Always" mode or the "Addressable" mode.

On top of the calculator are two 10783A Numeric Displays. At left is the 10740A Coupler.

Fourteen seven-segment LED indicators with left-hand decimal points allow ample capacity for displaying more than one axis of data. Six axis identifiers (A,B,C,X,Y,Z) are supplied with each display module and may be inserted into the specially designed front panel. As an example, one 10783A can display six digits with sign and decimal point for the X axis and five digits with sign and decimal point for the Y axis, with a space between the two numbers. The "X" and "Y" identifiers can be placed in the front panel below the appropriate digits.

The characters that can be displayed are the digits 0 to 9, a minus sign, the letter E and the decimal point. Front panel indicators include ON light, a light indicating when the 10783A is "Addressed" and an overflow light that indicates when more than 14 characters have been received. In an overflow condition, the 14 least significant digits are displayed. In addition to these indicators, there is a lamp test switch for checking all segments and indicators not already energized.

Flicker-free output is obtained by employing both input and output data storage. The display digits are strobed at a constant rate independent of input data transfer rate.
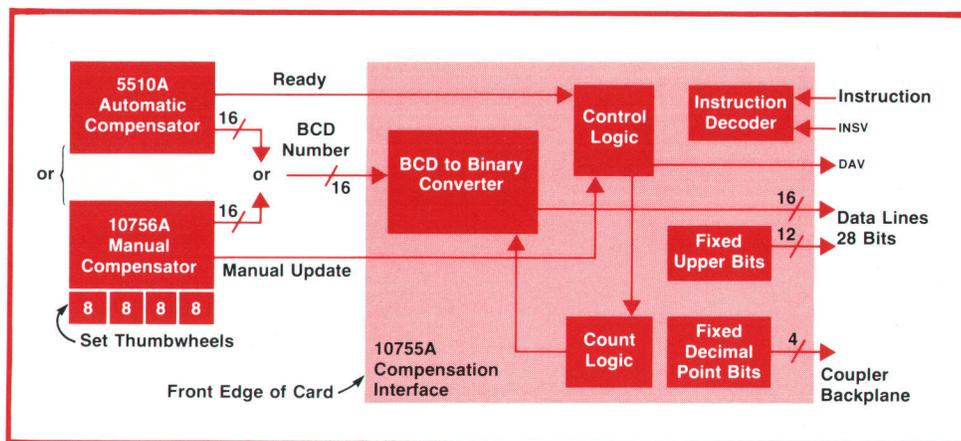
Ronald C. Jensen

Fig. 4. *The 10755A Compensation Interface card places an environmental velocity-of-light compensation factor on the coupler backplane. It gets this factor from the 5510A Automatic Compensator or from the 10756A Manual Compensator.*

preselected unit of measure.

Compensation Interface

Changing environmental conditions that result in a change in the index of refraction of air cause a change in the velocity of light and therefore in the wavelength of laser light. Accurate measurements require compensation for this effect.

Model 10755A Compensation Interface card (Fig. 4) places the required compensation factor on the coupler backplane when commanded by the system controller. Most coupler-based systems will include one compensation interface card.

The compensation interface gets the compensation factor either from the 5510A Automatic Compensator, a separate unit, or from the 10756A Manual Compensation module, which plugs into the coupler. The automatic compensator measures the temperature, pressure, and humidity of air and computes the index of refraction of air, n, and the compensation factor, $1/n$, which is between 1.0000000 and 0.9990000 for all earth-type atmospheres. Because only the four least-significant digits change, the compensator presents only these digits to the compensation interface card in binary-coded-decimal format on sixteen parallel lines. The compensation interface converts the data to a form usable by the laser transducer system and outputs it to the coupler backplane when commanded to do so.

In typical installations—workshops, laboratories, machine shops—the compensation factor can change over a period as short as a few minutes. The 5510A Automatic Compensator can compute a new number as often as twice each second. Where the environment is closely controlled, such as in metrology labs, the compensation factor changes very little during a day, and the data can be entered instead from a 10756A Manual Compensation module. This module presents the compensation factor, computed from a formula or derived from tables in a handbook,

to the compensation interface in BCD bit-parallel, digit-parallel format identical to that of the 5510A. A small cutout in the front panel of the coupler allows access to the thumbwheel switches that set the number, and an update pushbutton tells the compensation interface that a new number has been entered and should now be converted into the proper format for the backplane.

The 10755A Compensation Interface card recognizes two instructions, output and update. Update comes from the coupler backplane, from the manual module's pushbutton, during system reset, and after each output to the backplane.

When an update command occurs the interface card waits for the completion of the next compensator computation cycle. It then presets four BCD down-counters with the sixteen bits from the compensator. At the same time it presets four binary up-counters with a sixteen-bit binary word representing the least significant sixteen bits of the binary representation of 9990000. The BCD down-counters are then clocked down toward zero, and simultaneously the binary up-counters are counted up. When the BCD counters reach zero, the binary counters hold a binary representation of the lower sixteen bits of a binary representation of the compensation factor.

Operation with the manual compensation module proceeds in similar fashion.

In addition to compensating for the variable speed of light, the use of the compensation factor allows the operator to correct for thermal expansion of the part being measured or worked. All dimensions are normally referenced to their values at 68.0°F (20.0°C); at higher temperatures they measure longer or shorter than this, depending on whether the part has a positive or negative coefficient of thermal expansion. The 5510A Automatic Compensator has a special thermal probe for sensing part temperature. The coefficient of thermal expansion is entered on the front of the unit through a set of thumbwheel switches. The compensator does the required computation
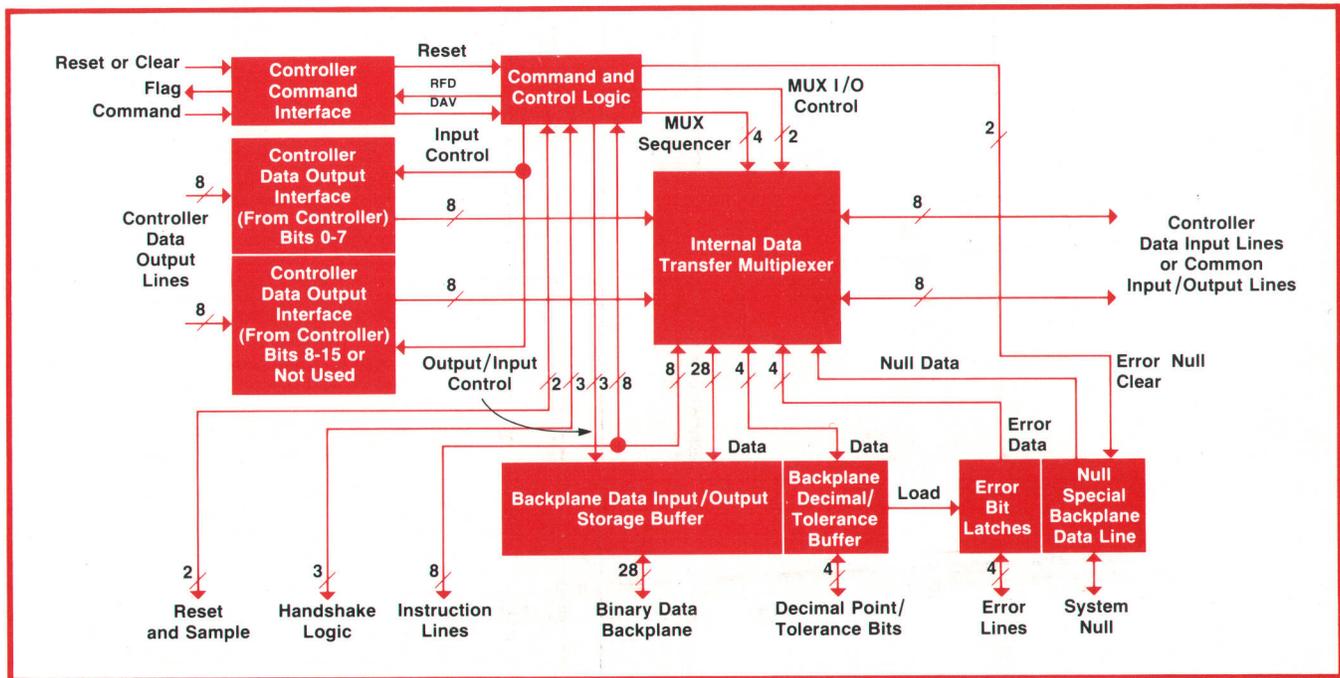
Fig. 5. *The 10746A Binary Interface is an I/O card suitable for interfacing the laser transducer system to a variety of computers and digital controllers.*

automatically and modifies the compensation factor accordingly. The same principle can be applied when using the 10756A Manual Compensation module.

A special check mode of the automatic compensator causes it to output the measured values of pressure, temperature, and humidity. These numbers can be placed on the backplane by the compensation interface, and can be accessed by the system controller for setup or system checkout.

Binary Interface

Along with the counter cards—one for each axis—and the optional multiplier and compensation cards, coupler-based systems must contain an input/output card, which acts as the interface to the system controller. The I/O card most suitable for a variety of computers and digital controllers is the 10746A Binary Interface (Fig. 5).

The binary interface transmits data to the controller in the form of two 16-bit binary words. There are sixteen lines for data output, so all sixteen bits may be transmitted in parallel. Alternatively, only eight lines may be used and the data sent as four eight-bit words. Data from the controller is sent to the interface card in the same format, using either the same lines or a separate set of tri-state buffered lines that are turned off during data output from the card.

Instructions come into the binary I/O card in the form of eight-bit words on the same lines as data.

The transfer of an instruction or data word is controlled by a command line, which indicates to the I/O

card that the bit pattern on the input lines is valid information, and a flag line, which indicates to the controller that the data bits have been accepted. When data is transferred to the controller the flag line indicates valid information and the command line indicates data accepted, a convention common to many I/O structures.

Because instructions and data share the same lines, the I/O structure has two modes of operation, called command mode and data mode. In the command mode, information from the controller is clocked into an instruction register and placed on the system backplane as an instruction to all the cards in the system, including the binary I/O card. The binary I/O card's control logic then interprets the instruction from the backplane and performs the required operation, if any. Once the instruction is clocked into the instruction buffer the controller is free to set up the next instruction even though the transducer system may not have completed execution of the preceding one. This allows operation with a fast controller in an interrupt environment.

There is a 36-bit data register on the binary interface card: 28 bits are used for binary data, four bits are used as a decimal point location buffer, and four bits are used as error status buffers. This register has two separate tri-state I/O ports, one for backplane input/output, and one for controller input/output.

When an instruction is received from the backplane to transfer data to or from the controller, the control logic switches to the data mode. In the case of

12

data input from the controller, the data register is sequenced by the control logic so that each time valid data is available, that data is clocked into part of the data register. If the card has been set (jumper selectable) for 16-bit words, the first 16 bits of data are loaded into the upper bits of the register with the four most significant bits being the decimal point location code. The next 16-bit word is loaded into the remaining half of the data register and the control logic immediately switches back to the command mode (error status bits cannot be loaded from the controller). If the card has been set for 8-bit words, the first word is placed in the upper portion of the data register and again the four most significant bits are the decimal point location. Then three more data words are accepted and placed in successively lower bit locations with the last word in the least significant eight bits. The control logic switches immediately back to the command mode after the fourth word.

If data is to be sent to the controller, the sequence is the same except that the control logic sequences the data register to put data onto the interface lines, most significant word first. If an error has been detected, the upper four bits (decimal point bits) of the transmitted data contain all ones to indicate that an error is being transmitted and the four status bits replace the data in the next four bits. This allows the same sequence to be used for error transmission as for regular data transmission.

A jumper-selectable data-mode-only configuration causes the binary interface to ignore commands from the controller. It will still transfer data, however, so it can be used as an I/O device for some peripheral other than the system controller.

HP-IB Interface

Model 10745 HP-IB Interface is the appropriate laser transducer input/output module for any system controller that is compatible with the HP Interface Bus, Hewlett-Packard's implementation of IEEE Standard 488-1975, a well-documented interface system (Hewlett-Packard Journal, January 1975). Such controllers include Hewlett-Packard Models 9815A, 9820A, 9821A, 9825A, and 9830A Calculators, HP 2100-Series Computers with the 59310A I/O card, or any HP-IB-compatible user-built controller. Fig. 6 is a block diagram of the HP-IB card.

The HP-IB card can operate as either a talker or a listener on the HP-IB. As a talker, it has two modes of operation. First, when addressed to talk, it outputs a string of nine ASCII* numeric digits followed by ASCII carriage return (CR) and line feed (LF) codes. A decimal point, also in ASCII, can occur anywhere in the string of digits.

The HP-IB card's second mode of operation as a talker is related to the service request capability and the serial poll mode. When an error in the laser transducer system is noted by any card, the card involved stores the occurrence in a buffer. When that card is instructed to output its data, it also outputs the contents of its error buffer. This error information is loaded into an error register on the HP-IB card and can only be cleared with a reset command. The presence of the error condition causes the HP-IB line called SRQ to be set true. The controller should be programmed so that, when it recognizes this condition, it executes a serial poll, that is, it untalks and unlistens every-

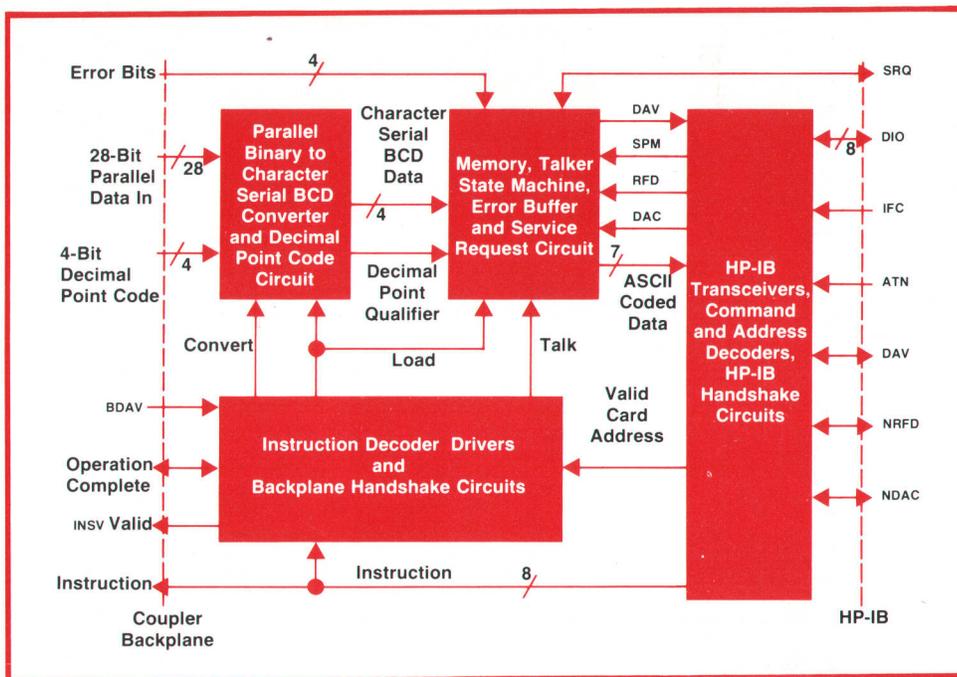*American Standard Code for Information Interchange

Fig. 6. *The 10745A HP-IB Interface is the laser transducer I/O card for system controllers compatible with the HP Interface Bus.*

thing on the bus, then addresses itself to listen and sends the universal command SPE (Serial Poll Enable). Then it begins polling devices on the HP-IB capable of responding to SPE by sequentially addressing them to talk. Responding to serial poll, the HP-IB card outputs an eight-bit status byte. The controller takes the decimal value of the status byte and examines it to see if bit 7, the service request bit, is set or not. If it is, bits 1 through 4 are examined to see what combination of errors has occurred. The controller may then send a reset command to clear the error register of the HP-IB card.

As a listener, the HP-IB card receives a four-bit wide command and a four-bit wide address and combines them into an eight-bit wide instruction that is sent out over the instruction bus on the backplane of the coupler. Each time its address buffer is loaded, the HP-IB card sets a backplane line called Instruction Valid or INSV to the true state to inform cards in the coupler to look at this instruction. Whenever INSV is true, the HP-IB card will not allow new data to be loaded into its command and address buffers. It sets the HP-IB line NRFD low whenever INSV is true and it is addressed to listen. This informs the talker on the HP-IB that the HP-IB card is not ready for data (NRFD). The controller can, if so programmed, unaddress the HP-IB card and service some other device on the HP-IB while the laser transducer is executing an instruction. This allows maximum use of the HP-IB when a fast controller is used.

There are two algorithmic state machines or ASMs on the HP-IB card. They operate essentially independently but because they share some common circuits

they do not operate simultaneously. One ASM controls the binary-to-BCD converter and the other controls the talker function.

Whenever an output instruction for another card occurs on the coupler's instruction bus, the HP-IB card takes the binary data, the decimal point position code, and the error flags that are put on the backplane as a result of the instruction and loads this information into its input data register, its decimal point register, and its error bit register, respectively. Then if a conversion instruction occurs, the conversion flip-flop is set and a signal is sent to the coupler backplane indicating that the instruction need not be held. The output of the conversion flip-flop is logically ANDed with a signal from the talker ASM signifying that it is not presently talking. The result is a qualifier input to the converter-control state machine. When this qualifier goes true, the converter-control state machine starts through its sequence of clocking the binary-to-BCD converter and loading its output into a random-access memory. Once started, it proceeds on its own until the conversion is complete, at which time it clears the conversion flip-flop.

The binary-to-BCD converter takes the 28-bit binary word in the input data register and, each time it receives a clock pulse, outputs a four-bit BCD character. This conversion takes place least significant bit first to most significant bit last. The 28-bit binary word translates to a nine-character BCD word and therefore it takes nine clock pulses to complete the conversion.

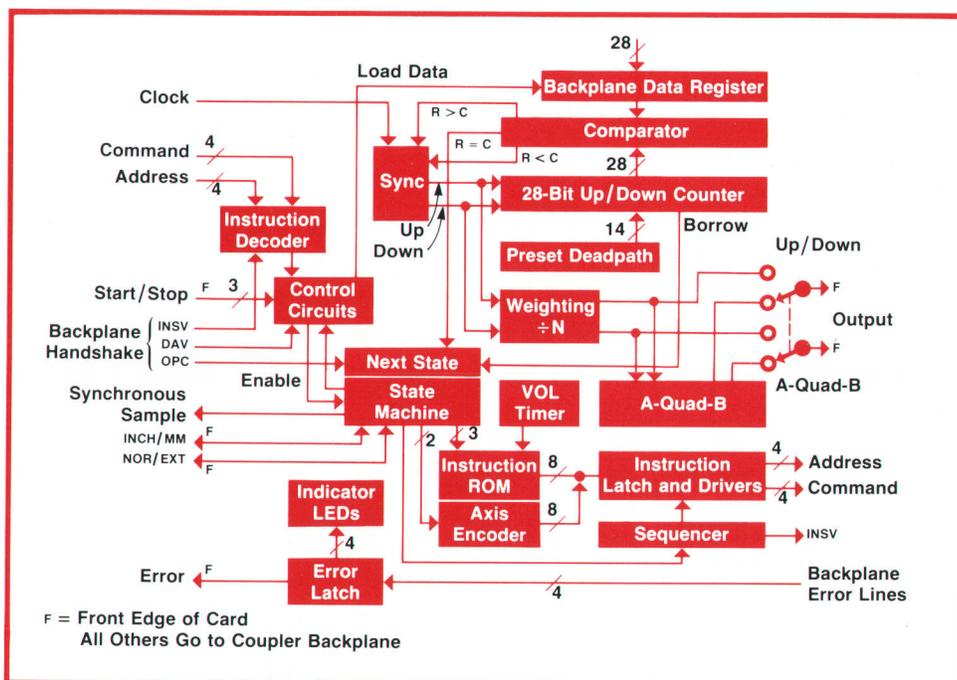Before clocking the converter each time, the converter-control ASM checks to see if the RAM address

Fig. 7. The 10763A English/Metric Pulse Output card is particularly appropriate for hardwired numerical controllers. One is required for each axis.

counter output agrees with the decimal point position code stored in the decimal point register. If it does, the converter is not clocked but the RAM address counter is advanced one. This leaves a space in the data string for the decimal point.

The converter-control ASM is clocked by a two-phase clock with a frequency of 3.33 MHz ±20%. Thus the time required for a complete conversion of the 28-bit parallel binary number to a nine-character BCD number with decimal point information is between 7 μs and 10.5 μs. The typical value is 8.4 μs. To date, there is no controller that can call for a conversion and issue a second command before the conversion is finished. But just in case one is built, the converter-control ASM and the talker ASM are interlocked so they will not try to operate simultaneously. In addition, the HP-IB card will hold up a data transfer on the backplane until it finishes converting the number. To take the converted data in the RAM and transfer it to the controller, all that is necessary is for the controller to address itself to listen and the HP-IB card to talk, and put the HP-IB into the data mode (ATN false). When this happens the talker ASM takes the four-bit-wide BCD data in the RAM, adds to it three additional bits to make it seven-bit ASCII, and outputs it on the HP-IB. The talker ASM monitors the NRFD line and the NDAC line on the HP-IB and drives the DAV line in accordance with the rules of the HP-IB.

Fringe-to-Inch/Millimetre Converter Systems

A third type of interface system, one that is particularly appropriate for hard-wired numerical controllers, is based on the 10763A English/Metric Pulse Output card. Such a system must have one 10760A Counter card for each axis, one 10763A English/Metric Pulse Output card for each axis, one 10761A Multiplier card, and one 10755A Compensation Interface card.

The 10763A becomes the system controller for the coupler backplane. It issues instructions to the counter, multiplier, and compensation cards, which convert the incoming reference and measurement signals into compensated displacement information in the form of a 28-bit binary number on the backplane. The pulse output card uses this data to generate up-down or A-quad-B signals representing total change in position.

The heart of the pulse output card is a 28-bit comparator, which compares the 28 bits of backplane displacement information with the contents of a 28-bit up-down counter (Fig. 7). Should the displacement number increase, the comparator enables up counts into the up-down counter until its contents are equal to the displacement. These up counts (or down counts for a negative displacement) each represent 0.1 micrometre (10 microinches in the case of English

units). These same count pulses are routed through a divide-by-N counter that allows the scaling factor to be selected by the user, so that each output pulse can represent any even tenth micrometre from 0.1 to 25.6 μm (or 10 to 2560 μin). A quadrature coding circuit allows the user to select A-quad-B output coding instead of the weighted up and down pulses. The A-quad-B output consists of two square waves in quadrature, with up/down information supplied by their relative phase: wave A lags wave B for an upward displacement and vice versa.

An algorithmic state machine (ASM) controls the internal functions of the card and generates the proper sequence of backplane instructions: synchronous sample; counter card output; multiplier card output; and return. If there are two, three, or more axes, the multiplier card is shared by the several pulse output cards, and control of the backplane is transferred from one pulse output card to the next in a regular sequence that is set during initial configuration.

A feature of the pulse output card is its ability to enter a preset number into the general-purpose counter card. This is used to allow for environmental compensation of the deadpath of the measurement axis. Deadpath is measured during machine installation and converted to a code that is entered into switches on the pulse output card. During initialization, the contents of these switches are preset into the up-down counter portion of the pulse output card. At the proper time in the initialization sequence, the pulse output card sends a count up instruction to its assigned counter card. When the pulse output card counts down to zero, it stops the counter, which now contains the deadpath, measured in quarter-wave fringe counts.

It is necessary to preset the pulse output card to a displacement count equivalent to the fringe count in the counter. This is easily done by causing the
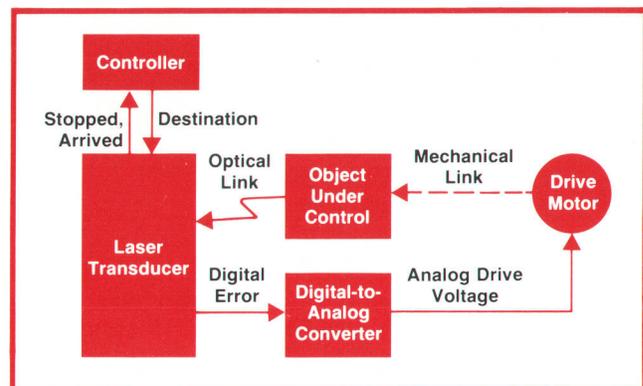

Fig. 8. *In closed-loop control systems like this one, the laser transducer system receives a destination from the system controller and then takes over the task of moving the object, notifying the controller only when the object stops or arrives at its destination.*

counter to output to the multiplier, and the multiplier to convert the fringe count to a compensated dead-path displacement and output it to the pulse output card. The pulse output card clocks this displacement into its 28-bit data register, and begins a special up count to equalize the up-down counter and the data register. During this time no pulses are sent to the external controller. When the special up count is complete a ready line notifies the external controller and the normal displacement data transfer begins. Should environmental conditions change, the new compensation factor will operate on both the measured displacement and the preset deadpath. This additional accuracy can be useful in some installations where physical limitations make it impossible to reduce the deadpath to the desired absolute minimum.

During each data transfer the pulse output card currently in control of the backplane looks at the four error lines on the backplane. Should one of these be true, an error latch is set and an LED lamp is lighted on the pulse output card to show which card has the error state and what kind of error it is. A user option allows the system to ignore errors on axes not currently being used, or to shut down the entire system at the first error on any axis in use, or any combination. Each pulse output card has an ERROR status line brought out to the front of the card; these may be looked at individually for each axis or wire-ORed together. A backplane reset resets the error latch.

The pulse output card also allows the user to select slow or fast maximum output pulse rate, and normal or extended resolution (×6 or ×10) for each axis individually.

Because each axis does a complete data input to pulse output cycle in approximately 11 microseconds (33 μs for a three-axis system) the output pulses are a real-time measure of the displacement.

Comparator Systems

A special case of laser transducer applications occurs in certain closed-loop systems, such as that shown in Fig. 8. The system controller sends the laser transducer system a digital representation of the destination of the object under control. The transducer system then takes over the task of measuring the object's position on a real-time basis, comparing it with the desired position, and controlling the drive motor. The controller is notified when the object arrives at the destination, or when it stops for any reason.

In systems like this, Model 10762A Comparator cards, one for each axis, replace the general-purpose counter cards described earlier. A binary multiplier card, a compensation interface card, and an binary I/O card complete the electronics package in the 10740A Coupler. Also required for each axis are an external digital-to-analog converter and a pulse converter or user-defined encoder.

Fig. 9 is a block diagram of the comparator card. The heart of the comparator is a 28-bit parallel subtracter with a built-in null decoder for the upper 24 bits. This circuit receives from the I/O card and stores a 28-bit digital representation of the object's destination along one axis. It also receives and stores a four-
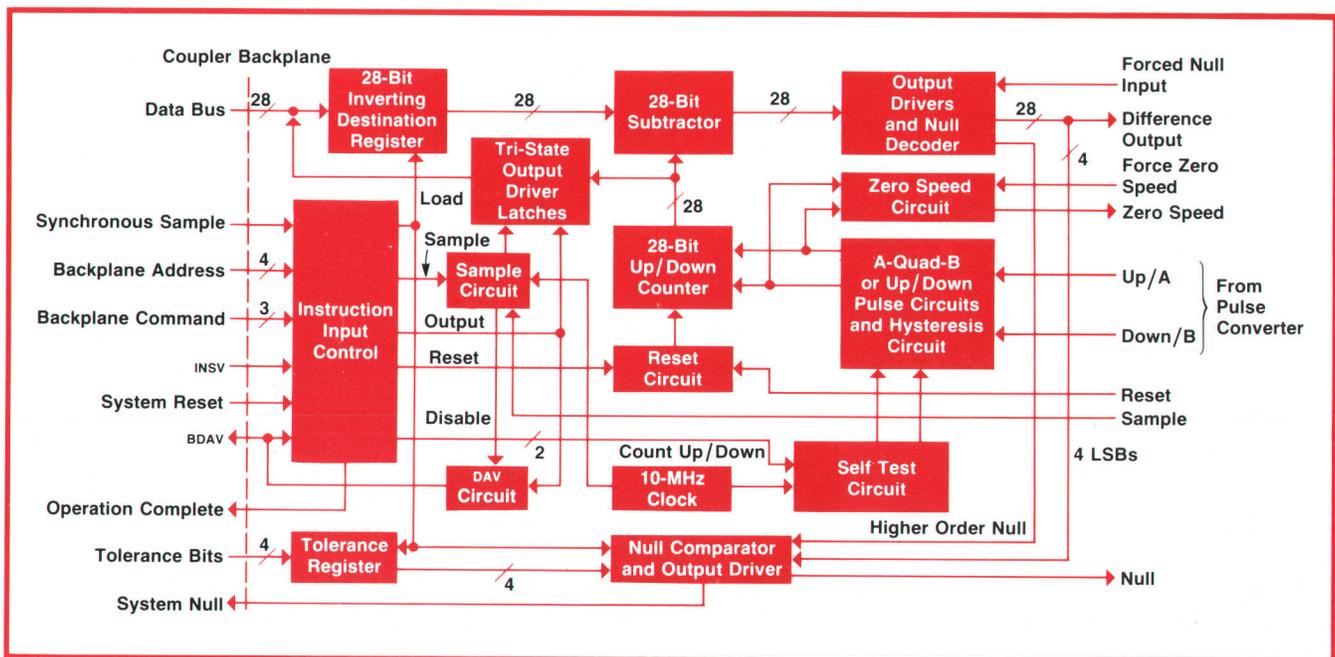

Fig. 9. *10762A Comparator cards, one for each axis, replace the general-purpose counter cards in systems like that of Fig. 8.*
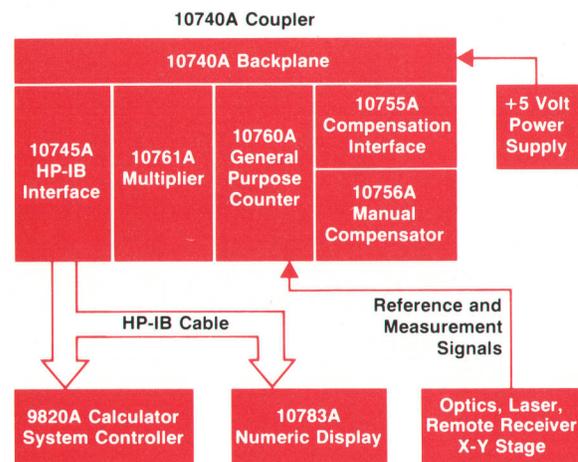
System Example: Calculator/Laser Controlled Measuring Machine

As an example of a complete electronics package for a laser transducer system, consider the following selection for the laser-controlled measuring machine pictured in Fig. 1, page 3.

For a three-axis measuring machine used for checking the dimensions of parts the system selected might be:

- One 9820A Calculator as a controller and data handler.
- Three 10783A Numeric Displays to display displacement information along the X-axis, the Y-axis, and the Z-axis.
- One 10745A HP-IB I/O card to get instructions into the system from the controller and to get displacement data and error information back out to the controller for distribution to the displays.
- Three 10760A General-Purpose Counters to measure the displacement along the three axes.
- One 10755A Compensation Interface with either a 5510A Automatic Compensator or a 10756A Manual Compensator plug-in for velocity-of-light compensation.
- One 10761A Multiplier required to convert fringe count into displacement measured in inches or millimetres.
- One 10740A Coupler with power supplies.

A system similar to this has been built in the laboratory. The 9820A program includes preset capability and complete error sensing and identification routines with printout of errors. The update rate is quite adequate for measuring machine applications. Since the slowest unit in the system is the 9820A Calculator, the advent of faster calculators in the future can only make the system run faster and more efficiently. In the short term, if high speed is needed, the 9820A could be replaced by an HP 21MX or a 2100 Computer. In this case the 10745A HP-IB I/O card might also be replaced with a 10746A Binary I/O card, which is more suited to the binary language used in computers. The 10746A can handle either 8-bit or 16-bit words while the 10745A is restricted to 8-bit words. A system would require half the number of I/O cycles using the 16-bit word to accomplish

data transfer and would therefore run faster and more closely match the internal architecture of 16-bit machines.

The block diagram here has been simplified to show only one axis. A typical 9820A program to measure the distance between two holes on a part would be as follows:

```
0:  DISP"GO TO GAGE";STP|-
1:  CMD"?U)","0O2V"|-
2:  DISP"PROBE TO HOLE 1";STP|-
3:  CMD"?U)","1X2XM30","?I5",RED13,A|-
4:  DISP"PROBE TO HOLE 2";STP|-
5:  CMD"?U)","1X2XM30","?I5",RED13,B|-
6:  B-A→C;FMT FXD11.6;CMD"?U1";WRT13,C|-
7:  END|-
```

bit tolerance code representing the degree of precision required in positioning the object.

The act of loading the tolerance register and the destination register causes the digital output to be forced to a null or zero difference regardless of the actual difference. This prevents the servo stage from taking off in some uncontrolled manner as soon as the destination register of the first comparator is loaded, and allows time for the comparators associated with the other axes to be loaded before allowing the system to move. However, this does not prevent the subtracter from working. As soon as the destination register is loaded, the comparator card begins to calculate the difference between the contents of a 28-bit wide up/down counter and the contents of the destination register. The difference appears at the input of the output-driver/null-decoders.

To start the system moving, either a synchronous sample command or an addressed sample instruction can be given. In addition to taking the present contents of the up/down counter and loading it into the comparator's output buffer, these commands release the forced null that was applied to the null decoder when the destination register was loaded. The digital difference in two's complement form then appears at the output of the comparator and is sent to the external digital-to-analog converter.

Under the influence of the drive voltage from the D-to-A converter the object begins to move toward the desired location. This movement is sensed by the laser transducer and translated by the pulse converter into up or down pulses. Fed into the comparator, these pulses cause the contents of the up/down counter to change in a direction that brings it closer to the value stored in the destination register. As this happens the digital difference between the desired location and the actual position is continuously fed out to the D-to-A converter to drive the object closer to the desired location. When the upper 24 bits of the up/down counter agree with the upper 24 bits of the destination register, the output of a four-bit comparator comparing the lower four bits of the dif-

ference output to the four-bit tolerance in the tolerance register is examined. When the difference output is within the tolerance a null signal is issued both to the outside world and to the coupler backplane. This null is wire-ANDed on the backplane with the same output from other comparators. This system null goes true only when all axes in the system have achieved their desired locations within their individual tolerances.
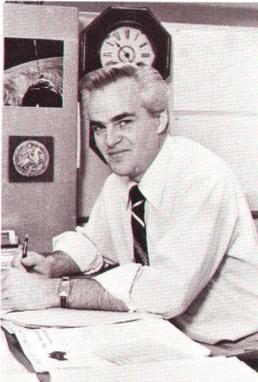
HP Computer Interface

An alternative to all of the systems described above is possible when the system controller is an HP computer.

Model 10741A Laser Transducer Interface is designed specifically to provide fast data transfer from 5501A Laser Transducer Systems to Hewlett-Packard 2100 Series Computers. Consisting of a circuit board that plugs directly into a computer input/output slot (no coupler is required), this interface is a particularly convenient and inexpensive means of laser transducer output. One board is required for each axis of measurement.

As with other output accessories, the 10741A Laser Transducer Interface receives the reference and measurement signals from the laser head and the 10780A Receiver, respectively; it also can accept some diagnostic information at the input connector. The two radio-frequency signals are directed to a dual-output mixer to generate up/down pulses, which are in turn recorded in a reversible counter. The accumulated count is then transferred to the computer, and the computer has the ability to reset the counter. **hp**

André F. Rudé

André Rudé is project manager for the 5501A Laser Transducer System. A native of Grenoble, France, he served in the French Air Force and holds an MS degree in micromechanics from the Ecole Supérieure de Micro-mécanique et Chronométrie. With HP for ten years of his 19-year professional career, he has been associated with HP's laser interferometer project since its inception. He's a certified technical translator and a senior member of both ASME and SME. At home in Los Altos, California, André is very active in church and youth athletics programs. People are his major interest, especially his wife and two sons, but also those of other countries and cultures that he's visited. Not one to waste time, he's also managed to take eight college-level courses in the last 12 months.

William E. Olson

Bill Olson came to HP in 1967 with four years' experience as a circuit designer. He has contributed to the design of several electronic counter products and designed the 10745A HP-IB Interface and the 10762A Comparator for the Laser Transducer System. Born in Chicago, Illinois, Bill served three years in the U.S. Marine Corps between the time he started college in 1955 and the time he received his BSEE degree in 1963 from the University of Illinois. Married and the father of three children, he's a classical guitarist, a weightlifter, and a student of archaeology and anthropology. The Olsons live in Fremont, California.

Robert B. Smith

Bob Smith designed and put into production many of the electronic parts of the 5501A Laser Transducer System. He's been with HP since 1972 and designed the 10525E Logic Probe before switching to the laser lab. A native of Malad City, Idaho, Bob graduated from Utah State University with a BSEE degree in 1972 and expects to receive his MSEE this year from the same school. He's married and lives in Cupertino, California, where he serves as an assistant Boy Scout leader. His recreational activities include photography, soaring and flying, and skiing.

Michael J. Ward

Mike Ward designed the 10780A Receiver, the compensation modules, and the English metric pulse output card for the laser transducer system. A 1966 BSEE graduate of Massachusetts Institute of Technology, Mike received his MSEE degree from MIT in 1968 and worked for five years in transmitter and receiver development for missiles and satellites before joining HP in 1973. He's active in the Professional Activities Committee of IEEE and serves as publicity chairman of the local IEEE section. Last year he was a member of a task force formed to study transit problems in Sunnyvale, California, his present home. Mike was born in Worcester, Massachusetts and grew up near Washington, D.C. He's single, a railroad enthusiast and an amateur radio operator.

Using a Programmable Calculator as a Data Communications Terminal

A discussion of the data communications capabilities of the HP 9830A Calculator, with examples of real-life applications.

by James E. Carlson and Ronald L. Stickle

BY ADDING AN INTERFACE cable and plugging in a pair of special read-only memories, the user of an HP 9830A BASIC-Language Programmable Calculator can convert his machine to a versatile data communications terminal. The calculator can be a time-sharing terminal with the ability to exchange programs and data with a timesharing computer, can act as a binary synchronous remote batch terminal to a remote computer, and can communicate with another calculator or terminal.

Intelligent Terminal?

A question frequently asked is, "Is the 9830A an intelligent terminal?" Probably the best answer is, "No, it's an intelligent calculator that has data communications capability." Most intelligent terminals might be better described as preprogrammed terminals for specific applications. Typically, the intelligent terminal may be used to enter data from keyboard to storage based on a form, or to emulate the functions of popular hardwired terminals, the most prominent being the IBM 2780. Although the 9830A Calculator can emulate the IBM 2780 and can be used to enter data based on a form, this is not its primary function. It performs best as a stand-alone processor that has data communications capability.

Although designed as a stand-alone machine, the 9830A has several capabilities that allow it to be conveniently converted to a terminal. These include alphanumeric character manipulation (strings), a general input/output structure, 4,000 to 16,000 bytes of expandable buffer memory, and a page-width, high-speed printer. For timesharing applications, its typewriter-like keyboard is easier to use than one on which the letters and numbers are arranged in another format. For remote batch, the calculator mass memory allows efficient use of the communication link and provides ample storage for input and output

data. The 9830A's program language is BASIC, which is well known to users of timesharing systems.

Another feature that aids the 9830A in its role as a terminal is a set of 20 user-definable keys, called special function keys, that are available to store often-used sequences like telephone numbers or user sign-on codes. Only a single keystroke is needed to dial a telephone number, to send a user code, or to perform an entire sign-on sequence including dialing.

Data Communications Options

When Hewlett-Packard first introduced the 9830A, the intent was to fill a gap between programmable calculators and computers. The 9830A is designed as a stand-alone computing system that is compact, inexpensive, and easy to use. Options are provided by plug-in read-only memory (ROM) blocks.

A terminal ROM, one of the first ROMs introduced, gave the calculator its original capability to act as a timesharing terminal. With the terminal ROM the calculator acted like a teleprinter. Programs could be prepared off-line and edited in the calculator memory, and programs could be received into memory from a timesharing system.

However, users were not satisfied simply to emulate a teleprinter. Requests were received for a mode that would allow blocks of data to be sent to a computer automatically. Also, the calculator was growing as a small computing system. The addition of a disc with a maximum capacity of 4.8 million bytes, a hopper-fed card reader, and a medium-speed line printer meant that more and more data could be handled. The need arose to move locally collected information to a larger computer, or to input data from a larger data base to a local data base at the calculator.

To satisfy these needs, a more powerful modem/

autodialer interface was designed, along with three plug-in data communications ROM blocks (Fig. 1). The Interface Control ROM (Data Comm. 1) must be installed for any data communications application. To convert the calculator to a remote batch terminal, the Binary Synchronous ROM (Data Comm. 2) is also needed. For timesharing applications, the Interactive ROM (Data Comm. 3) is used along with the Interface Control ROM.

Timesharing Terminal

The Interactive ROM converts the calculator into a timesharing terminal. It does this by taking control of the keyboard operating system. Normally, when a key is pressed, a character is displayed. Adding the Interactive ROM puts the modem interface into the keyboard loop. Now the calculator waits for keystrokes from either the keyboard or the timesharing modem and displays this information on the LED display. A full display buffer (80 characters) or a carriage return causes the information to be printed on the calculator printer.

A special function key, labeled TRANSMIT on the template shown in Fig. 2, is programmed by the ROM to send characters typed into the display. Two other special function keys emulate the teleprinter SHIFT and CONTROL keys to generate control characters that may be required by a timeshared computer to sign on, for editing, to break, or to end input sequences.

Unlike standard teleprinter or CRT-based terminals that use paper tape or tape cassette to send programs, the calculator memory is used to send and *receive* programs. Instead of being prepared on paper tape, programs are entered directly into the calculator memory and edited line by line or character by character using the powerful editing features of the 9830A Calculator. Programs do not have to be in 9830A-compatible BASIC because the calculator syntax checking is bypassed by the ROM. For example, FORTRAN, COBOL, or lines of text can be entered and edited. Once the program has been prepared, it may be stored on tape or disc as if it were a program for the calculator. To send the program to a computer, it is simply listed to the modem as if it were being listed on the printer. To receive programs to the calculator memory, a listing is requested from the computer. This is normally done by sending a LIST or similar command. To route the program to memory instead of the printer, the user sends LIST from the display by pressing the special function key labeled SAVE.

The calculator memory limits the size of programs that can be sent or received to about 15,000 to 16,000 characters. Programs longer than this can be sent or received by dividing them into segments that will fit in the memory and doing partial listings. Or, programs may be sent and received using 9830A peripheral storage if the computer system has the capability to accept one line at a time and send an X-ON or
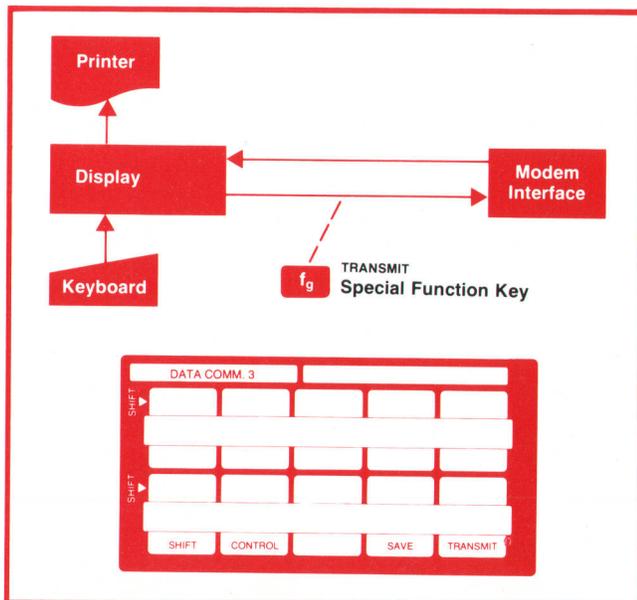
similar prompt to ask for the next line. In this case, a BASIC program can be written for the calculator to take program lines input from the keyboard and store them as data on tape cassette. Then the tape is read and the program sent to the computer by another BASIC program (or a subroutine), with the calculator listening for the prompts.

Because the controlling software that enables the 9830A to act as a timesharing terminal is in ROM, the calculator can run local BASIC programs while on-line with a computer. Since the modem interface can be treated like any other peripheral, a local program in the calculator can interact with a user program at a timesharing system. This opens a new range of applications in which locally collected data is sent to a program at the computer. Data from the computer may also be sent to a BASIC program at the calculator. The latter capability has been used to plot data points received from a computer on a calculator plotter. Timesharing users often want to plot information received from the timeshared computer. This is not always possible because the computer system may not have the proper plotter software driver. The 9830A, with its plotter peripheral, can be used to receive and plot data from a computer whether or not the computer has a plotter driver.

The accounting department at HP's Loveland, Colorado Division uses a 9830A Calculator with the 9862A Plotter to generate several local financial reports. The calculator is also used as a timesharing terminal to access programs and data on an HP 2000 Computer System in Palo Alto, California. To plot data received from the HP 2000, the program shown in Fig. 3 is used. The receiver portion of the program is quite simple. It sends a command to the computer to start sending the information to be plotted. Then the TREAD instruction puts the calculator in a receive mode to read data into a series of strings until a "<" character is detected (this is determined by EOT 74 in line 30). When the information has been received, the user signs off from the computer using the calculator as a teleprinter-like terminal. To plot the data a CONT 70 is executed. The remainder of the program contains a search algorithm to examine the series of string variables and plot the X and Y data points. The program could be enhanced by adding a subroutine at the end to label the axes from the calculator.

Another example of a 9830A serving as a terminal is in the calculator manufacturing systems area at HP's Loveland facility. Here a 9830A Calculator with mass memory communicates with an in-house HP 3000 Computer to transfer master scheduling data from the 9830A's disc drive to a 9-track magnetic tape at the HP 3000. In this case, no telephone lines or modems are used. Instead, the calculator is wired directly to a multiplexer port of the computer.

```
10 DIM A$[255],B$[200],C$[200],D$[200],E$[200],F$[200]
20 DIM X$[1],Y$[1],Z$[1]
30 EOT 74
40 TWRITE( 1,ASC)"YES",15,
50 TREAD( 1,ASC)A$,B$,C$,D$,E$
60 END
70 X=19
80 OUTPUT (Y$,130)X;
90 X=10
100 OUTPUT (Z$,130)X;
110 X=94
120 OUTPUT (X$,130)X;
130 FORMAT B
140 SCALE 0,9999,-9999,9999
150 I=POS(A$,"PLTL")
160 A$=A$[I+4]
170 GOSUB 330
180 IF X3=-1 THEN 240
190 IF  NOT X8 THEN 210
200 PEN
210 PLOT X1,X2
220 PRINT X1,X2,X8
230 GOTO 170
240 A$[LEN(A$)+1]=B$
250 B$=C$
260 C$=D$
270 D$=E$
280 E$=F$
290 IF LEN(A$)=0 THEN 310
300 GOTO 170
310 PEN
320 END
330 IF LEN(A$)<5 THEN 460
335 X8=POS(A$,Z$)
340 IF  NOT X8 THEN 460
350 X9=POS(A$[X8]," ")+X8-1
360 IF  NOT X9 THEN 460
370 IF X9-X8>1 THEN 420
390 A$=A$[X9]
391 X8=2
401 A$[POS(A$,Y$)]=A$[POS(A$,Y$)+3]
402 A$[POS(A$,Y$)]=A$[POS(A$,Y$)+3]
410 GOTO 350
420 X1=VAL(A$[X8+1,X9])
430 A$=A$[X9+1]
440 X9=X9-X8+1
450 GOTO 500
460 X3=-1
470 IF LEN(B$)#0 THEN 490
480 A$=""
490 RETURN
500 X2=VAL(A$)
510 A$=A$[X9-1]
520 X8=POS(A$,X$)
530 X8=(X8=1)
540 IF  NOT POS(A$,X$) AND  NOT POS(A$,Y$) THEN 460
550 X8=0
560 RETURN
```

Program Notes

Lines 10 through 30 reserve storage for data and set the end of transmission character that will end the READ in line 50.

In Line 40, a YES is sent to the computer to start the program at the HP 2000 to send the data. Received information is input by the TREAD in line 50 to a 1055-character buffer.

The program from line 70 is continued when off-line to search the strings of data, find the X and Y values and do the plotting. Lines 70 through 130 put special control characters into X$, Y$, Z$ for later use in searching A$.

X$ = X-ON
Y$ = Line Feed
Z$ = Control S

Fig. 3. *A BASIC-language program for a 9830A Calculator used as a timesharing terminal to plot data received from an HP 2000 Timeshared Computer System.*

The portion of the program shown in Fig. 4 sets up the calculator as a terminal, signs on to the computer, and then calls the FCOPY routine to copy master schedule files onto the tape. Earlier in the program, the 9830A set up the files on the mass memory in the proper format for the magnetic tape. When the data transfer is complete, the 9830A performs a program-controlled sign-off from the computer and beeps three times (GOSUB 290 in line 2420).

The previous method of doing this same job required a substantial amount of keypunching to put the printed output of the 9830A master scheduling program on cards for input to the HP parts allocating system on an IBM 370 computer. Now, the 9830A data is put on 9-track tape via the HP 3000, and the tape is carried to the IBM 370. Eventually, the system will be used to return data from the HP 3000 to the 9830A's disc drive.

The 9830A can also operate as a terminal to non-HP timesharing systems. One current application involves sending information digitized from contour maps to a computer, which merges this information with other inputs to plan where and how deep to mine for coal. In another application, data collected

```
1000 G$=""
1010 OUTPUT (G$[1,1],*)
1020 GOTO 1040
1030 X$[X]=X$[X+1]
1040 X=POS(X$,G$)
1050 IF X THEN 1030
1060 WRITE (S,970)X$,10,10
1070 RETURN


2000 IF X$#"YES" THEN 1970
2010 L=13
2020 SYSTEM 1,2400,8,NONE,ASY1,FD
2030 EOT 21
2040 WRITE (1,970)L,
2050 TREAD( 1,ASC)X$
2060 WRITE (1,970)"HELLO EAGLE.PROD"L,
2070 TREAD( 1,ASC)X$
2080 GOSUB 1000
2090 WRITE (1,970)";"L,
2100 TREAD( 1,ASC)X$
2110 WRITE (1,970)";"L,
2120 TREAD( 1,ASC)X$
2130 WRITE (1,970)"FILE TAPE;DEV=TAPE;REC=-39,1,ASCII"L,
2140 TREAD( 1,ASC)X$
2150 IF  NOT POS(X$,":") THEN 2130
2160 WRITE (1,970)"RUN FCOPY.PUB.SYS"L,
2170 TREAD( 1,ASC)X$
2180 IF  NOT POS(X$,"FILE COPIER") THEN 2160
2190 WRITE (S,*)"GOTO 3000 CONSOLE.  MOUNT THE TAPE."LIN1
2200 WRITE (S,*)"PRESS: CONSOLE INTERRUPT"LIN2"TYPE THE REPLY"LIN2
2210 GOSUB 290
2220 WRITE (1,970)"FROM=;TO=*TAPE"L,
2230 TREAD( 1,ASC)X$
2240 IF POS(X$,"ANSWER YES") THEN 2290
2250 WRITE (1,970)"EXIT"L,
2260 TREAD( 1,ASC)X$
2270 IF  NOT POS(X$,":") THEN 2250
2280 GOTO 2130
2290 WRITE (1,970)"YES"L,
2300 TREAD( 1,ASC)X$
2310 READ #2,1
2320 READ #2;X$
2330 WRITE (1,970)X$,L,
2340 TREAD( 1,ASC)G$
2350 IF X$#":EOD" THEN 2320
2360 WRITE (S,970)G$,10,10
2370 EOT 15
2380 WRITE (1,970)"BYE"L,
2390 TREAD( 1,ASC)X$
2400 TREAD( 1,ASC)G$
2410 IF POS(X$,"KNOWN COMMAND") OR POS(G$,"KNOWN COMMAND") THEN 2380
2420 GOSUB 290
2430 DISP "SELECT AN 'OUTPUT' KEY"
2440 END
```

Program Notes

The subroutine in lines 1000 through 1070 finds a carriage return in the received data buffer X$ and prints the information following this carriage return.

Prior to line 2000, the BASIC program has taken information in one format on mass memory and converted it to the format for the HP 3000 tape.

Lines 2010 through 2120 perform the necessary sign-on to the computer. Lines 2130 through 2360 set up the computer to accept the data and route it to tape as well as informing the 9830 operator to mount the tape.

Sign-off occurs by the program in lines 2370 through 2420. GOSUB 290 causes the calculator to "beep" informing the operator that the data transfer is complete.

Fig. 4. *A BASIC-language program to send data from the 9830A calculator's disc drive to a 9-track magnetic tape drive at a remote HP 3000 Computer System.*

from several digital voltmeters controlled by the calculator is normalized and forwarded to a central computer from a remote test site.

Remote Batch Terminal

Transferring data asynchronously as in the previous examples is usually successful only when the amount of information communicated is small or when a direct line connection is provided, as in the HP 3000 example. Sending data without any means of error checking and recovery is usually not successful when there is noise on the line or when accidental disconnects occur. In such cases the calculator may continue to listen to a dead line, or a complete data transfer may be aborted and have to be restarted. Where large amounts of data must be transferred, a means of providing for transmission error detection and recovery is required. Also, communication will be more economical if a higher data transfer rate is available. For the 9830A Calculator, error checking and higher speeds are achieved by the remote batch terminal configuration.

With ROM and BASIC-language software, the 9830A can emulate an IBM 2780 Remote Batch Ter-

minal. The emulation takes place on two levels. Operations defined for binary synchronous protocol are performed by the Binary Synchronous ROM. These include a CRC-16 checksum algorithm, code conversion, insertion of the necessary sync and other control characters, and automatic responses to a block received correctly or in error. Functions related specifically to the 2780 terminal are incorporated in a BASIC-language program. These include setting up a 400-character buffer, record delimiters, the option to suppress spaces, and the general operations of the terminal.

Other parameters can be modified in the BASIC program to tailor the calculator terminal to an application. A 132-column line printer can be substituted for the 80-column printer, or the 80-column printer can be used with characters beyond 80 continued on a second line. Input can be from a card reader, keyboard, tape cassette, or disc storage. Output can go to a printer, tape cassette, or disc. The BASIC program employs special function keys with the template shown in Fig. 5 to select the operation to be performed. The block diagrams in Fig. 6 illustrate the flow of information through the calculator.

The special function key approach allows the user to operate the 9830A batch terminal in a logical manner. For example, to build a job for the computer, the user presses the CARDS TO STORAGE key. This allows him to type card images from the keyboard onto tape cassette or disc. When the input is complete, he presses the SIGN-ON key and calls the computer. The SIGN-ON key is programmed to send a card for an IBM system of the form:

/*SIGNON   REMOTE 20

The remote number 20 is keyed in at the calculator by the user. The 9830A will print a message +SIGNED ON when the computer acknowledges the sign-on card. At this point, the user can press MODEM TO LIST or MODEM TO STORAGE to receive information from the computer. To send the job that was prepared off-
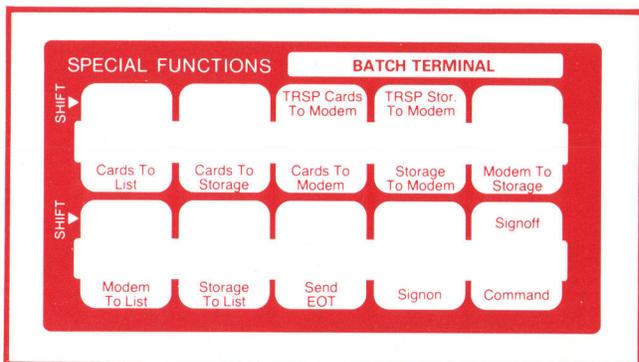

Fig. 5. *Special function key template for the Binary Synchronous ROM (Data Comm. 2), which converts the 9830A Calculator to a remote batch terminal.*
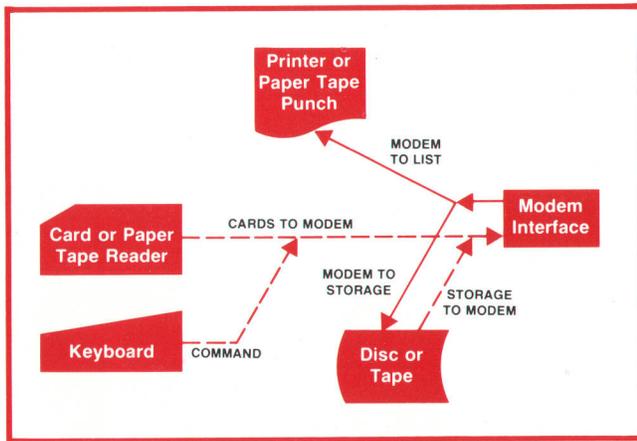
22

Fig. 6. *9830A batch terminal on-line operations. Special function keys cause information to be transferred in various ways.*

line, the user can press STORAGE TO MODEM to send code from the 9830A storage media to the computer.

Other functions that can be performed by the 9830A Batch Terminal include:

- Off-line listing of 9830A storage files or cards (CARDS TO LIST, STORAGE TO LIST)
- Send cards to computer (CARDS TO MODEM)
- Send a one-card command keyed in by the user (COMMAND)
- Send a HASP sign-off card (SIGNOFF)

In addition, the editing programs can modify files in 9830A storage that have been built by using the CARDS-TO-STORAGE mode.

Applications of the 9830A as a remote batch terminal usually employ the calculator as part-time terminal, part-time programmable calculator. BASIC-language applications programs in areas such as accounting, engineering, statistics, medicine, and education are available for the calculator. When a particular user's application exceeds the capacity of the calculator, the problem is transferred to a computer using the calculator as a remote job entry terminal. Another typical application includes transmitting data files collected locally to a larger data base on a computer. Or, data stored on a computer system may be transferred to the calculator for analysis or local report generation.

The only real limitation of the calculator as a terminal is that it cannot act as a multi-point terminal in an interactive mode. It must be connected via a point-to-point link using binary synchronous communication procedures. Data transfer occurs on a file-by-file basis rather than the inquiry and response mode associated with timesharing systems. However, the calculator can collect data either directly keyed in by an operator, or input from instrumentation, cards, or paper tape, or digitized from drawings. Later, under

program control, it can initiate a call to a computer or be called by a computer to transmit the data.

In the calculator products laboratory at the HP Loveland Division, a 9830A calculator tied into a mass memory system with three other calculators is used as a remote job entry station. Jobs, consisting of the control cards for an IBM computer and ALGOL-language programs, are put on mass memory files as card images directly from the 9830A keyboard. The "cards" are then sent via telephone lines to an IBM computer near Boulder, Colorado, where the ALGOL programs are run. The resulting output is then retrieved via the calculator directly to another mass memory file. The job output can be printed or saved for future reference.

The BASIC-language emulation program can be revised to include preprocessing and postprocessing at the 9830A. Preprocessing might include collecting and organizing information into a format required by an applications program at the computer. As a postprocessor, the calculator might generate locally formatted reports based on raw data received and stored.

One example of post-processing with the calculator used as a batch terminal is numerical control (NC) tape preparation by a midwest-based manufacturer. Programs written in the APT (Automatic Programming of Tools) language and JCL (Job Control Language) are stored as card images on a tape cassette. This is done directly from the calculator keyboard under control of a BASIC-language program. The BASIC program not only allows generation of the card images but also editing, including deleting or inserting cards. When the tape cassette is ready, the calculator signs on to the company's IBM computer to send the card images. Output from the APT processor is a listing with job statistics and EIA data for an NC control tape. The job statistics are routed to the printer; but the EIA data is put on tape cassette and later used off-line to generate the final punched tape on the calculator's peripheral tape punch. Further post-processing includes reading the tape via a peripheral tape reader and verifying the NC program by plotting the NC machine movements on the calculator's X-Y plotter.

Calculator to Calculator

Calculator-to-calculator communication provides the widest range of options. Full-precision data arrays can be transferred from one machine to another at rates up to 9,600 bits/second in either asynchronous or synchronous mode. BASIC programs can be transferred from the memory of one machine to the other, and for asynchronous rates up to 1,800 bits/second, one calculator can remotely control another.

Programs can be loaded, run, or stopped and peripherals can be activated. If, for example, a calculator is connected to a disc containing several programs, a user at another calculator can call up and access programs from the disc via the first calculator. For data transmission where error immunity is required, two calculators can be configured as two remote batch terminals using binary synchronous communication procedures.

Calculator-to-calculator communication can be employed simply to move data from one machine to another. In a typical system, a calculator interfaced to a blood analyzer in one clinical laboratory collects data on blood samples and stores this information on disc files. Another clinical laboratory 40 miles away performs the same data collection onto tape cassettes. This data is also forwarded via 300 bit/second acoustic couplers to the disc files at the first calculator. Thus, the calculator disc is used as a local data base for the two laboratories.

Ronald L. Stickle

Ron Stickle came to HP in 1967 after four years in the U.S. Navy. Five years later, in 1972, he received his BSEE degree from Colorado State University. He designed the 11284A Data Communications Interface and defined the algorithms for the three Data Comm ROMs, and is now a production engineering coordinator at HP's Loveland, Colorado facility. Born in Denver, Colorado, Ron lives in Loveland, 70 miles north. He's a water and snow skier and enjoys backpacking and hunting with his two sons, ages 10 and 11.

James E. Carlson

Calculator product manager Jim Carlson originally joined HP in 1966, just after receiving his BSEE degree from Iowa State University. Drafted into the U.S. Army six months later, he served for 21 months, then enrolled at the American University in Washington, D.C. Dividing his time between his studies and work as a systems engineer and programmer, he received his MS degree in business in 1971. He rejoined HP in 1973. Born in Riverside, California, Jim grew up in the midwestern U.S. and now lives in Loveland, Colorado. He's married and has a small son. Currently restoring a 1953 MGTD roadster, he also enjoys skiing, amateur radio, camping, woodworking, and local Toastmasters activities.