HEWLETT-PACKARD JOURNAL

OCTOBER 1987

HEWLETT-PACKARD JOURNAL

October 1987 Volume 38 • Number 10

Articles

Research Report

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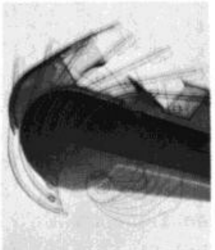
Administrative Services, Typography, Anne S. LoPresti • European Production Supervisor, Michael Zandwijken

In this Issue



In our computerized society, there's always a prodigious amount of data in motion, much of it on the voice-frequency circuits of the telephone network. To judge a voice-frequency circuit's suitability for carrying data, instruments called transmission impairment measuring sets (TIMS) transmit test signals and measure a circuit's effect on these signals according to standards set up by the CCITT or the Bell System, depending on the country. There's a trade-off in this picture—while a circuit is being tested, it isn't available for data transmission. The paper on page 4 describes the design and theory of operation of a new kind of TIMS, the HP 4948A In-Service TIMS, that does away with this test-or-use decision. The ITIMS attaches to any voice-frequency access point in a circuit, and without disturbing normal data transmission, measures the parameters that other TIMS measure. The measurements the ITIMS makes aren't the ones described in the standards, but the results are comparable. Its technique, which makes interesting reading, involves imitating a modem and setting up a model of the circuit in parallel with the modem.

Two months ago, in August, we presented the design story of two advanced handheld calculators, the HP-18C and the HP-28C. This month we have papers on the portable thermal printer for these calculators (page 21) and the infrared link between printer and calculator (page 16). The link is interesting because it's one-way only. The calculator sends data all the time, never knowing whether the printer is there. Link reliability is ensured partly by pacing the data transmissions so that even the slowest printer can keep up. As the paper on page 24 informs us, the production of the HP-18C and HP-28C called for technologies that were new to HP's calculator production operations, and for extensive use of computer-aided design (CAD) and manufacturing (CAM). The cover photo shows the printer with a CAD system simulation of its paper door rotation.

The explosion in medical knowledge has raised fears among medical educators that the amount of knowledge a medical student needs to absorb may be outstripping the time available to teach it. Harvard Medical School is attacking this problem with their New Pathway curriculum, which makes heavy use of HP computers, electronic mail, and computer-based training modules. On page 28, four Harvard staff members describe the new curriculum and some early results.

HP Laboratories' Bristol Research Centre is investigating formal methods of specifying system behavior, properties, and requirements, and is developing tools to provide machine support for rigorous software engineering. On page 37, two Bristol researchers report on their Framework for Program Development, a tool that facilitates the documented construction of correct programs.

-R.P. Dolan

What's Ahead

An Important Notice to Our Readers

After this month the Hewlett-Packard journal will become a bimonthly publication. Next month, November, there will be no issue. Subsequent issues will be in December, February, April, June, August, and October. Each issue will be about twice the present size. This change will allow us to take advantage of some economies of scale and put a greater variety of articles into each issue. Current subscribers will continue receiving their copies, and subscriptions will continue to be free. As always, your comments are welcome.

The December issue, in addition to the annual index, will have papers on the technical details of MPE XL, the commercial operating system for HP Precision Architecture computers such as the HP 3000 Series 930 and 950. Also featured will be the design of the HP 8780A Vector Signal Generator and the HP 8980A Vector Analyzer, which are stimulus/response instruments for testing digital microwave radio systems, and the HP 3065AT Board Test System.

The HP Journal encourages technical discussion of the topics presented in recent articles and will publish letters expected to be of interest to our readers. Letters must be brief and are subject to editing. Letters should be addressed to: Editor, Hewlett-Packard Journal, 3200 Hillview Avenue, Palo Alto, CA 94304, U.S.A.

An Infrared Link for Low-Cost Calculators and Printers

by Steven L. Harper, Robert S. Worsley, and Bruce A. Stephens

MANY OF HP'S HANDHELD CALCULATOR customers have told us of their need to create a permanent record of their calculations easily. The need seems to be particularly acute for users of financial calculators. A banker or real-estate agent often wants to give a client a printed record of loan information or perhaps an amortization table showing interest paid and remaining balance. Because of this customer feedback, printing capability was high on the list of design priorities for the HP-18C Business Consultant.[1]

There are two approaches to providing this feature. One method is to design another model of the calculator with a built-in printer. The earlier HP-91 and HP-97 Calculators[2] are examples of this approach. Although the portability of the unit suffers somewhat, this is a good solution for the customer who uses the printer a lot and knows of the need for this capability before buying the calculator. It is less ideal for the person who really wants full portability or didn't realize the need for a printing capability until after the calculator was purchased. For this individual the other approach, that of designing a separate accessory printer which connects to the calculator in some way, is the better solution. This approach also yields somewhat lower development cost and a shorter design schedule. The HP-41C Calculator uses this method,[3,4] and the decision was made to design an accessory printer for the HP-18C also.

Interconnection Method

One very critical design area for such a printer is the means of interconnection to the calculator. The HP-IL interface[5] is used in the HP-41C for connection to a number of peripherals, including an accessory printer. This would have provided much more capability than was needed for a simple printer-only interface, and would have cost more. In addition, we had received a number of complaints from customers about the inconvenience of the cables for the interface and battery recharger with our portable products. With this in mind, we began to investigate the possibility of a wireless interface for a printer powered by disposable batteries.

Infrared transmission seemed to be the only wireless technology that allowed the use of low-cost, low-power, and readily available components. Infrared remote-control units for television sets and videocassette recorders have been in use for years. Their transmitting element usually consists of one or more infrared light-emitting diodes driven so as to produce short bursts, each containing a few pulses of invisible infrared light at a wavelength of 940 nm. The pulses within each burst have a repetition frequency of about 40 kHz and their intensity is proportional to the current through the diode(s). Information is encoded by varying the time between bursts.

The receiver uses a photodiode which acts as a weak current source with an amplitude proportional to the incident light intensity. A sensitive gain-controlled preamplifier provides frequency selectivity, demodulation, and conversion of the photodiode current to logic voltage levels. Since the HP-18C Calculator already has a 32.768-kHz oscillator for its time and alarm functions, our infrared link uses 32.768 kHz as the infrared modulation frequency, rather than the slightly higher value used by conventional remote-control units.

Silicon photodiodes respond to a broad range of wavelengths, including most of the visible spectrum. To reduce unwanted signals, the photodiode in the receiver is often encapsulated in a material that is opaque to visible light, but transparent to the longer infrared wavelengths. Various kinds of optical filter materials are also used as windows in front of the photodiode to reduce extraneous light further by moving the cutoff wavelength still closer to 940 nm. The infrared receiver in the printer for the HP-18C uses both of these techniques. However, incandescent lights and sunlight still have strong components in the infrared range. The modulation of the bursts allows some frequency selectivity that reduces this dc and low-frequency optical interference still further to provide a higher signal-to-noise ratio and an improvement in the distance over which the link will operate reliably.

Implementing the Link

The cost of adding the infrared transmitting circuitry in the calculator is minimal. This is especially important since it allows us to include that part of the link in every calculator without penalizing the customer who does not want the printing capability. Otherwise it would be necessary to resort to a more expensive and complex plug-in module system, which would likely add as much or more cost to the calculator, even without the module.

Unfortunately, the receiver end of the link is substantially more expensive. The infrared preamplifier chip requires several discrete components and a regulated supply. The additional printed circuit board area needed was much more than could be accommodated in the calculator. Because of this, it was necessary to make the infrared link a one-way-only interface—the calculator is the transmitter and the printer is the receiver.

While cost and size considerations made this decision obvious, it nevertheless represented a trade-off in link performance. The printer cannot send handshake signals to the calculator, indicating readiness to receive more data. Because of this, after enough characters are transmitted to fill the printer's buffer, the calculator must carefully pace subsequent transmissions so that even the slowest printer can keep up. When the printer has fresh batteries, it can print at a rate of slightly more than one line per second. When the batteries are near the end of their useful life, the rate is reduced to just over one half line per second. It would have been nice to be able to run the printer from a regulated supply rather than directly from the batteries so that the speed would be more constant. Unfortunately, the current requirements are quite high (up to 1.5A average, 3A peak while printing) and the inclusion of such a supply would have escalated the cost of the printer far beyond its design objectives. In any case, the user will seldom notice this trade-off since most printing with the calculator is done in segments smaller than the size of the 200-character print buffer. Under these conditions, the printer performs as fast as it is able, given the current state of the batteries. For longer print segments, the first eight lines or so print as fast as the printer can go, and then the system slows to a rate of slightly more than one half line per second.

One of the most important specifications for any interface is the maximum data rate. For this infrared link, the rate is slightly less than 80 characters per second. Other important parameters are distance and directional sensitivity. Commercial infrared remote-control units typically have a range of thirty feet or more. This is neither necessary nor desirable for calculator-to-printer communication. The infrared link obeys a square-law response with respect to distance, that is, doubling the range requires four times the transmit drive current for a given receiver sensitivity. This quickly becomes a problem for the calculator's power supply. In addition, a long-range capability in this application creates a potential problem where one individual's calculator might interfere with someone else's printer nearby. The minimum distance is about 18 inches to allow comfortable desktop operation, but the maximum range is no more than a few feet to avoid such problems.

The infrared light-emitting diode in the calculator has an integral molded plastic lens which forms a somewhat directional radiation pattern. At an angle of slightly less than thirty degrees from the directional axis of the pattern, the intensity falls to half its maximum value along the axis. The photodiode in the printer has no lens and its sensitivity is much less directional. Its response is proportional to the perpendicular area facing the source and is therefore a cosine function. At sixty degrees the response will be half the maximum. If the calculator's batteries are fresh, and the calculator and printer are lined up facing each other, the range is about four feet. On the other hand, if the batteries are about ready for replacement and the calculator faces thirty degrees away from the printer, the maximum distance over which the link will operate is about 18 inches. Naturally, obstructions in the path and reflections can significantly change these values.

How the Interface Works

Fig. 1 diagrams the circuitry used for the infrared link. A combination of hardware and firmware in the calculator generates the proper gated pulse waveform to drive the infrared light-emitting diode. A resistor connects the microprocessor port to the base of a bipolar transistor that acts as the driver device to handle the relatively high current peaks required. In the HP-18C, the series resistor limits the light-emitting diode current to about 80 to 160 milliamperes, depending on the state of the batteries. While these currents are fairly high, it may be possible in the future to integrate the transistor driver on the microprocessor chip, and thus reduce the size and cost of the transmit end of the link in the calculator even further.

The transmitted infrared signal is converted into a current by the photodiode in the printer, and then into a very small differential voltage by the pull-up and pull-down resistors. Two coupling capacitors feed this signal into the preamplifier IC. In the preamplifier are two externally compensated gain stages with automatic gain control. The pulse bursts then pass through a tuned synchronous demodulator stage and an output integrator and pulse shaper before

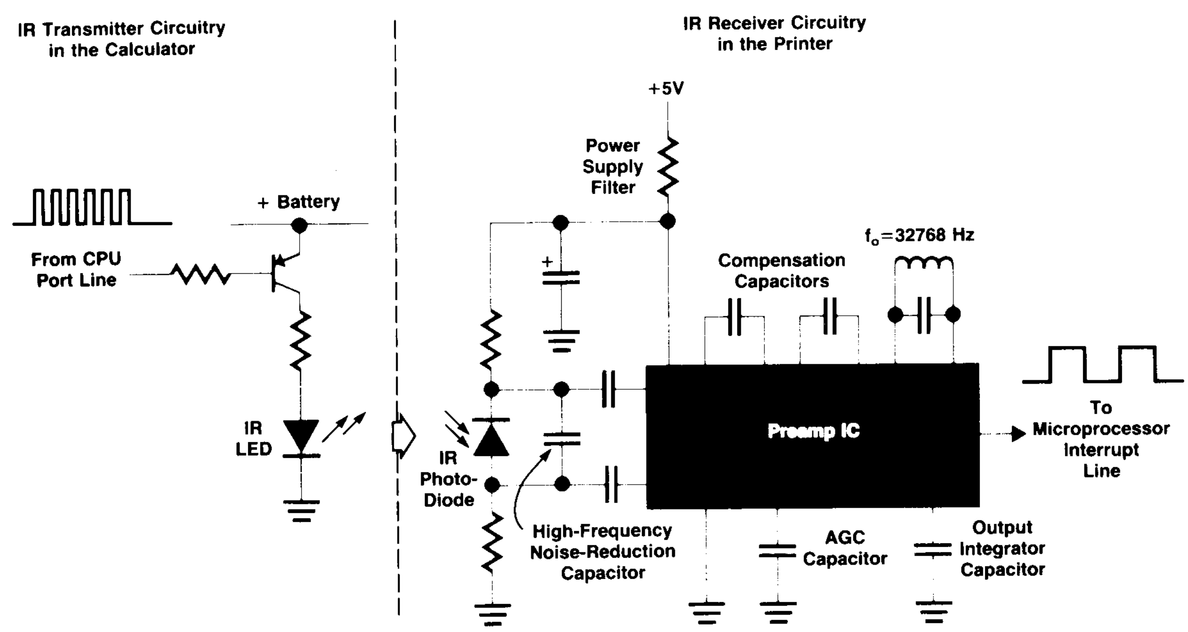


Fig. 1. *Infrared link schematic diagram.*

reaching the logic signal levels required to drive the interrupt line of the printer's microprocessor.

Electrical interference is a special problem for the extremely high-gain preamplifier. Careful printed circuit trace routing for power supply and ground lines and power supply filtering are essential. The typical solution to this problem is shielding, but this is particularly difficult for a small portable product with a nonmetallic case and no connection to earth ground. Several circuit configurations were tried before an acceptable solution was found. A capacitor is added in parallel with the photodiode, its value carefully chosen such that high-frequency noise is shorted to ground and prevented from getting into the first stage of the preamplifier without attenuating the 32.768-kHz signal frequency appreciably. This increases the link range substantially.

The calculator sends bursts of infrared light that are modulated with a 32.768-kHz square wave to produce 6 to 8 pulses of light in each burst. Fig. 2 shows two typical bursts. Each 32.768-kHz cycle consists of a 15.26-μs pulse of light followed by a 15.26-μs pause.

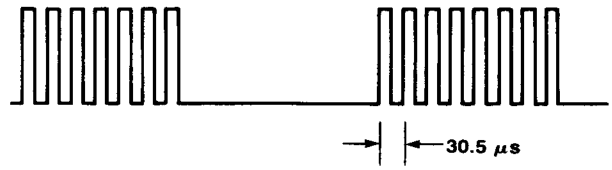


Fig. 2. *Data is transmitted as a series of bursts of infrared light, each burst formed by six to eight pulses of energy at a pulse repetition rate of 32.768 kHz.*

Coding

The data is encoded in bit times which are subdivided into half-bit times. A bit time is defined as 28 periods of a 32.768-kHz waveform (approximately 854.5 μs). Time intervals are measured from the leading edge of the bursts. There are three kinds of bits (see Fig. 3 for an example):

- One bit. A one bit is defined as a burst at the beginning of the first half-bit time with no burst in the second half-bit time.
- Zero bit. A zero bit is defined as no burst in the first half-bit time and a burst at the beginning of the second half-bit time.
- Start bit. A start bit is defined as a burst at the beginning of three consecutive half bit times, an otherwise illegal sequence. Start-bit bursts can have six to nine 32.768-kHz pulses of infrared light.

Each frame consists of a start bit followed by 12 data bits. The first four data bits are the error correction bits and the remaining eight bits are the byte being transmitted. There must be a delay of at least three half-bit times between frames, measured from the end of the last bit time of a frame to the leading edge of the start bit of the next frame. This gives a maximum data rate of about 78 bytes/s. An example of a complete frame is shown in Fig. 3.

Error Correction

Two kinds of errors are expected to be the most likely: bits that are missed entirely and noise bursts introduced in addition to the correct data bursts. The bit decoding routine treats bit times with extra bursts (noise) as missed bits since it does not know which burst was data and which burst was noise. Therefore, the error correction code only has to correct one kind of error—missed bits. Flipped bits (1 ⇝ 0 or 0 ⇝ 1) are much less likely since this requires a noise burst to occur in the opposite half-bit time of a missed burst, so these errors are not corrected.

Each error correction bit encodes the parity of a subset of the data bits, allowing correction of up to two missed bits by checking the parity of separate sets of bits. The correction bits (H1 to H4) are set as the even parity of the data byte ANDed with the following masks:

Bit	Mask
H1	01111000
H2	11100110
H3	11010101
H4	10001011

Unidirectional Communication

The unidirectional infrared interface permits the calculator to talk to the printer, but the printer cannot communicate back. This eliminates the need for any receiver circuitry in the calculator. Conversely, the printer is saved the circuitry needed to transmit back to the calculator.

As a result of the unidirectional nature of the communication, the calculator has no direct information on the status (or even the existence) of the printer. It can merely transmit bursts of infrared light in such a manner that the printer can handle them. The most critical piece of information that is missing is whether the printer's buffer is full. The printer has a 200-character buffer. The calculator must make sure that this buffer never overflows. The printer is capable of emptying the buffer at a rate of so many lines per second, but the number of lines in the buffer depends on how many characters there are per line.

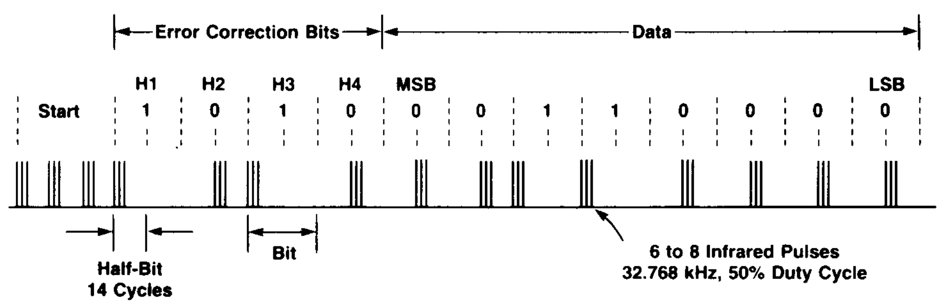


Fig. 3. *Example of infrared message frame.*

A simple solution would be simply to wait long enough following each transmission of a line to be sure that the printer has finished. This doesn't take much advantage of the printer's buffer and causes the calculator to remain inactive for prolonged periods of time. What we would really like is to have the calculator strive to keep the printer's buffer full. After a long pause without printing the printer's buffer is certain to be empty, so several lines can be transmitted immediately and the printer should be able to buffer them and print them as fast as possible. Only when the calculator has sent enough lines to fill the printer's buffer should the calculator have to wait to transmit more data.

A truly perfect algorithm would have the calculator keep track of when each of the lines was transmitted and how many bytes were in each line. However, this requires too much memory. Instead, some simplifying assumptions are made. All lines are assumed to contain 25 bytes (24 characters plus an end-of-line byte), which means that the printer's buffer will hold up to eight lines. Rather than keeping track of when each line was sent, a simple line counter and a record of the time when the last line was sent are used. The counter is incremented each time a line is sent and the time of that transmission is saved. Before sending a line, the calculator checks how much time has elapsed since the last line was transmitted. It then calculates how many lines the printer should have printed during that time and subtracts that number from the line count. If the count indicates that the buffer can now hold another full line, the calculator sends the line and saves the current time as the last transmission time and updates the line count to include this newly transmitted line. If the buffer cannot hold another line yet, the calculator waits and repeats the above process until the buffer empties enough to accept another line.

Assuming that the printer can print at the specified rate, this algorithm is foolproof. Since not all printers print at the same rate and they tend to slow down as their batteries deteriorate, the calculator must never send lines faster than the slowest printer can print while running at the lowest acceptable battery level. Hence, since most printers empty their buffers more quickly than the calculator is allowed to transmit, they will often pause while the calculator is waiting to send the next line.

Critical Timing in the Link

Another challenge in the printer transmission firmware was the timing of the bursts of infrared energy needed to transmit a character. As the development of the printer progressed along with the calculator, the need for accuracy of the burst timing became quite apparent. Each character is transmitted as a series of bursts of infrared energy modulated at 32.768 kHz. Each transmitted byte (frame) is divided into 27 subparts which include the start bits, redundantly encoded data, and error correction information. This scheme is designed to maximize the printer's ability to recover garbled frames.

The most common problem with infrared transmission is dropout of the infrared signal. Some of the transmitted bursts may not be detected by the printer if the calculator and printer are at the limits of their range or if something momentarily blocks the transmission path between them. The encoding scheme used works well for recovering from lost bursts, but only if the bursts are timed accurately enough so that the printer does not get completely out of synchronization with the calculator. This would cause the rest of the bits in the frame to be incorrect.

To achieve the required timing accuracy, the calculator's microprocessor needs to start each infrared burst within a 4-μs window. Since the nominal clock rate is 617 kHz, the microprocessor must not be more than one cycle away from the perfect time. The clock is generated by an LC oscillator whose frequency varies slightly from unit to unit and with changes in temperature and battery voltage. The calculator also contains a 32.768-kHz crystal oscillator that the firmware can use to calibrate the loops used to time infrared bursts. The exact number of processor cycles required between bursts is calculated, and by using variable cycle count instructions, this exact number of cycles is achieved. This calculation is performed before each line is sent to guarantee that the clock has not drifted significantly. The flowchart in Fig. 4 shows what is done.

The printer receiver decodes the incoming infrared bursts by measuring the time intervals between successive bursts. This time-interval measurement is subject to four sources of error:

1. After being detected by the photodiode, the incoming bursts go through a preamplifier, which introduces additional timing error. The input to the preamplifier consists of a series of 15.26-μs-wide pulses of current separated by pauses. The preamplifier may not respond to the bursts of pulses in exactly the same way every time. Its output might go true on the nth pulse in one burst and on the $(n+1)$th pulse in the next burst, which would make the interval between bursts at the preamplifier output look 30.5 μs too long. Similarly, the output could go true on the $(n+1)$th pulse in one burst and on the nth pulse in the next burst, which would make the interval look 30.5 μs too short. Therefore the error from the preamplifier is approximately ± 30.5 μs.
2. The output of the preamplifier goes to the interrupt pin of the printer's microprocessor. Since there are places in the printer's firmware where the interrupt must be temporarily disabled, the interrupt can be delayed up to 13 processor cycles (about 34 μs). Depending on whether this happens on the first or last pulse of an interval, the interval can look longer or shorter by 13 cycles.
3. Once the interrupt occurs, the interval between interrupts is measured using a timer in the CPU. Since the timer ticks only every 32 cycles (about 84 μs), additional error is introduced by this granularity. For example, an interval that is really 11.3 timer ticks long will be measured as either 11 or 12 ticks long depending on when it occurs relative to the timer ticks.
4. The final error comes from the printer's oscillator speed variations. Since an LC oscillator is used, the frequency varies somewhat from printer to printer. Therefore, the actual time interval represented by the measured number of timer ticks varies with processor timing. A fast processor will show more timer ticks for a given interval than a slow processor.

The receiver code uses the time interval since the last interrupt as an index into a fixed timing table to determine whether the current interrupt is for a one bit or a zero bit. The time interval must be adjusted by five ticks if the last bit was a zero since the interrupt for a zero occurs at the midpoint of the bit time rather than at its beginning. The ability to correct up to two missed bits means that the table must be seven half-bit times long to cover the bit sequence 1XX0 where X indicates a missed bit. Table I shows the range of timer ticks calculated for each bit-to-bit interval, taking into account the above errors as well as the number of ticks actually used in the timing table.

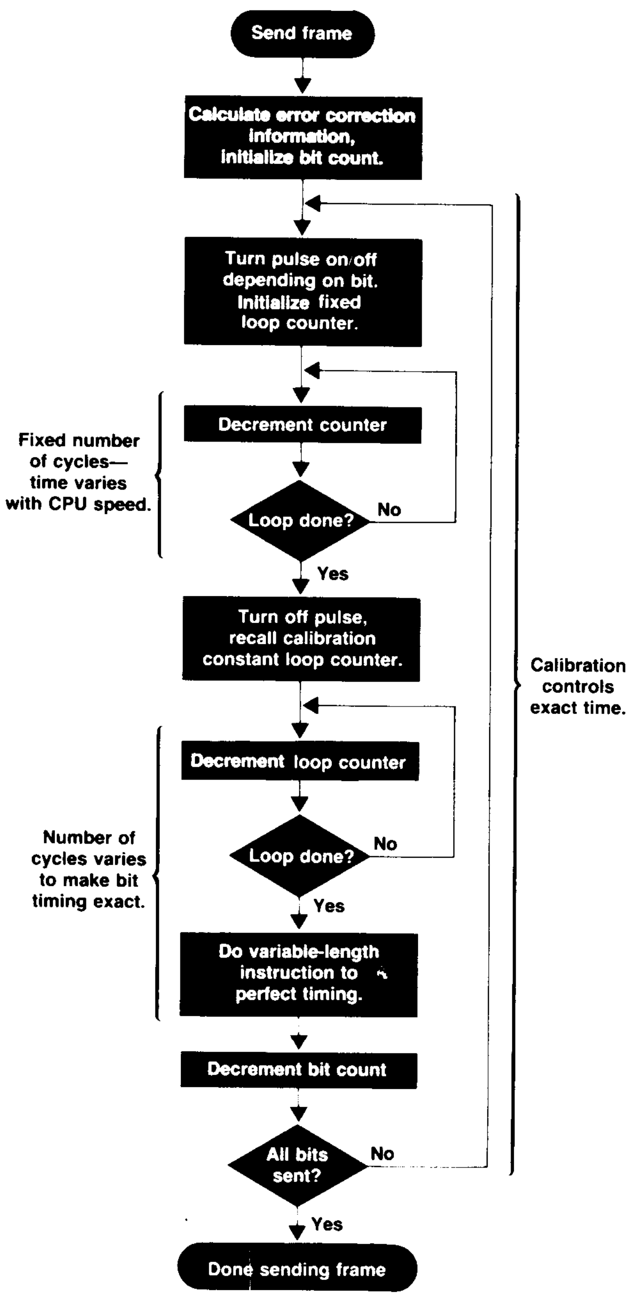


Fig. 4. *Flowchart of algorithm used by calculator to adjust data transmission timing.*

Table I
Timing Table

Processor Ticks	Table Ticks	Bit Received	Comments
0-2			Too short, ignore it
3-7	3-7	X	Two pulses in same bit time, treat as missed bit
8-12	8-12	1	
13-17	13-17	0	
18-23	18-22	X-1	Missed bit followed by a one bit
23-28	23-28	X-0	Missed bit followed by a zero bit
28-34	29-33	X-X-1	Two missed bits, then a one bit
33-39	34-39	X-X-0	Two missed bits, then a zero bit

The burst timing resyncs on each received burst since the time of each interrupt is saved as the starting point of the time interval between it and the next interrupt. Start-bit timing is handled as a special case. The start bit must be received correctly before the code looks for the 12 data bits. After the frame is received, the byte is checked using the error correction bits and corrected if necessary.

Looking at an earlier version of the calculated timing table, it became apparent that the calculator must transmit the infrared bursts very accurately to get reliable decoding of received frames since the intervals overlap when bits are missed. For example, if 34 processor ticks occur between bursts, the cause is two missed bits followed by either a one or zero bit, but the printer would interpret it as the latter. Table I includes the maximum allowed error in the calculator transmission as well as the printer errors. The overlap of intervals leaves a possibility of improper bit decoding, but a statistical simulation showed that the probability of this occurring is very low.

Acknowledgments

A number of people deserve special mention for the contributions to the infrared printer project. Dave Rabinowitz was the project manager. Mechanical design was handled by Dave Smith and Jack Muranami, who explain some of the mechanical design decisions in the article on page 21. Gary Podwalny did the industrial design. Theresa Gibney's efforts in manufacturing were especially important. Grant Salmonson did the production test tooling. With the help of Ng Say Ban, David Shum, and Tan Zing Chiou at Singapore, a difficult transfer to production went very smoothly. Herbert Ting provided strong support from the QA department.

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4. R.D. Quick and D.L. Morris, "Evolutionary Printer Provides Significantly Better Performance," *ibid.*
5. R.D. Quick and S.L. Harper, "HP-IL: A Low-Cost Digital Interface for Portable Applications," *Hewlett-Packard Journal*, Vol. 34, no. 1, January 1983.

A Low-Cost Wireless Portable Printer

Based on a unidirectional infrared transmission path, this small thermal printer can provide hard copy of HP-18C and HP-28C calculations.

by David L. Smith and Masahiko Muranami

THE HP 82240A INFRARED PRINTER (Fig. 1) is a portable battery-powered thermal printer capable of printing a maximum of 24 columns of alphanumeric characters or 166 columns of continuous graphics per line. Designed for use with an HP-18C or HP-28C handheld calculator,[1,2] the information to be printed is transmitted to the printer by the calculator using an infrared beam. This transmission method is discussed in detail in the article on page 16.

The printer uses HP's standard 58-mm-wide black-printing thermal paper. The 2-inch-diameter, 80-foot-long roll will provide about 6000 lines of print. User controls include power, print intensity, and paper advance switches. The HP Roman8 character set is provided.

Power is supplied by four commercially available AA-size batteries and can be supplemented by an ac adapter with a common barrel-shaped plug. The unit can accept adapters with ac or dc output. With full power the printer is capable of printing 0.8 line per second. One set of fresh batteries will print up to one roll.

The HP 82240A measures approximately 7.25 inches long by 3.5 inches wide by 2.5 inches tall. It weighs about

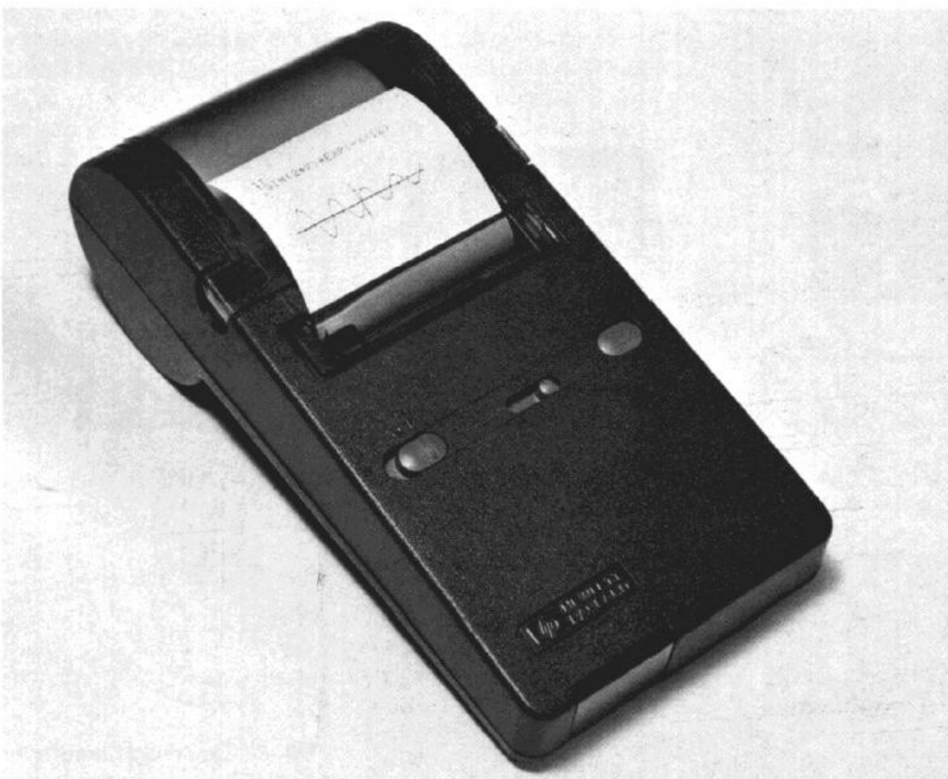

Fig. 1. *The HP 82240A Infrared Printer is a battery-operated printer designed for use with the HP-18C and HP-28C Calculators. The need for connecting cables is eliminated by using an infrared beam for data transmission.*

one pound when loaded with a full paper roll and batteries. A manual, paper roll, and batteries are included with the printer.

Product Design

The components of the HP 82240A can be divided into several general categories (see Fig. 2): printer mechanism, printed circuit assembly, battery contacts, electrostatic discharge protection, and plastic parts.

The development time for the HP 82240A was rather short because of its scheduled announcement along with the HP-18C. One factor that enabled quick development was the decision to purchase an OEM printer mechanism. The mechanism was chosen for compactness, quiet operation, and graphics printing capability. Its cost accounts for one third of the total part cost of the printer. Testing was conducted to ensure acceptable life, environmental, and drop-survival performance. Based on qualification test results, the manufacturer agreed to modify the mechanism to meet our drop test and package drop test requirements.

Other parts such as switches, CPU, and interconnects were chosen for low cost and savings in development time.

Two battery springs were designed to connect the batteries to the printed circuit board. Nickel-plated beryllium copper was chosen for high strength and corrosion resistance. The 3.3-by-4.5-inch single-sided printed circuit board is a departure from recent double-sided and/or hybrid board technology used in HP's handheld products. Lower cost was the main reason for this decision.

Attention was paid to efficiency and manufacturability throughout the design process. A CAD/CAM system was used from initial layout to drawing generation. Components of the printer such as plastic parts, metal parts, and the printed circuit board were designed as wireframe models. To ensure proper interaction among the parts, purchased components such as the paper roll, batteries, printer mechanism, switches, photodiode, and ac socket were also recreated in the data bases. Where necessary, these models could be manipulated to determine feature locations and to check for fit and interferences. The rotating motion of the paper door, for example, was simulated to determine its pin location in the bottom case and its snap detail in the top case (see Fig. 3). Application of CAD/CAM methods to the design process greatly increased confidence that all components would perform together as intended.

Early in the design process, manufacturing engineering advised that parts allowing layered assembly were more desirable. An effort was made to design plastic parts that held components in place during assembly, thus eliminating as many two-handed operations as possible. The solution chosen uses snap fits and slip fits throughout the product and allows assembly from the bottom case up. The battery shorting bars and contacts snap into the bottom case to allow manipulation of the assembly without dislocating them. The ESD protection components and printed circuit assembly are located by screw bosses. The keycaps slip onto the switch actuators and the printer mechanism is secured. Two screws locate the mechanism within a small tolerance band to eliminate the possibility of paper jams. The ac adapter receptacle and infrared window snap into the bottom case, after which the top case is slipped over the whole assembly. Six screws hold the cases together to ensure acceptable drop performance. The cosmetically sensitive paper door and paper tear-off window are snapped into place at the end of the assembly process.

Custom tooling for plastic parts was another area in

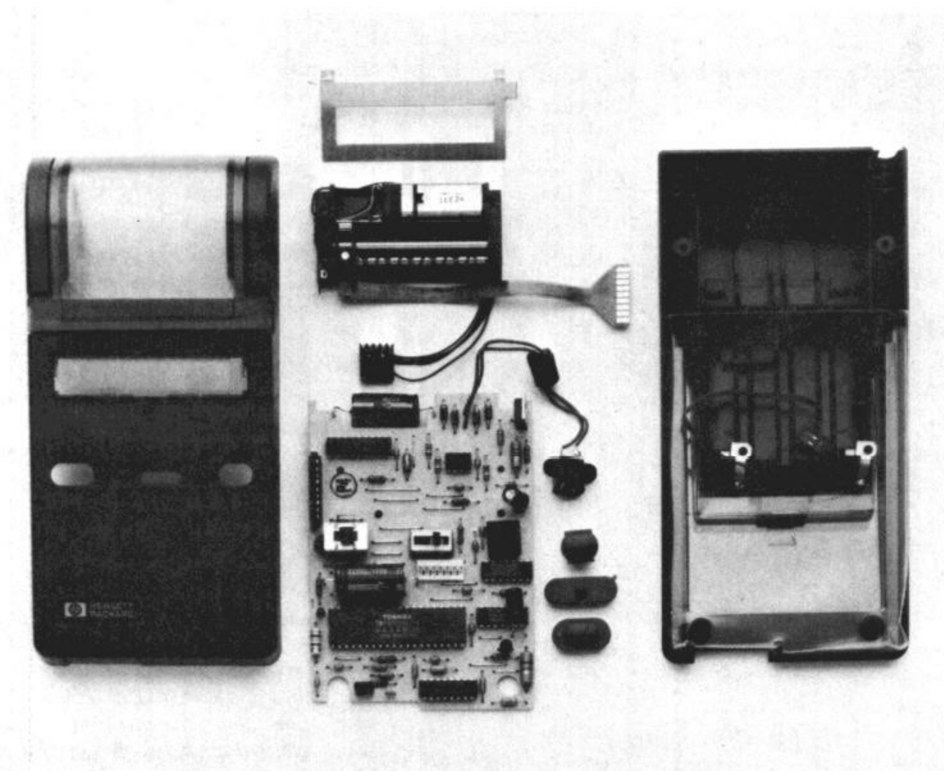

Fig. 2. *Components used in HP 82240A.*

which CAD/CAM played a major role. The plastic injection molds for the top and bottom case were built entirely using computer-aided-manufacturing techniques. The wireframe data base from R&D was transferred to a similar system in manufacturing. The mold designers used the part data base to create the mold data base. No part drawings were necessary, since the data base contained the required tooling information. Waterline locations, inserts, ejector plates and all electrode designs were completed on the system. The complex shape of the case parts would have made conventional calculations time consuming and difficult, but the system made number-checking trivial. Details such as the external radii along the intersection of a curved surface and a drafted plane were programmed and cut on a CNC (computerized numerical control) milling machine with great accuracy. With conventional techniques, milling such details exactly as the print specifies is nearly impossible and very time consuming. Complete tooling for the top and bottom case was manufactured in seven weeks, compared to quotes of nine to twelve weeks from outside vendors without CAD/CAM capability. Design modifications were also conveyed to the mold designers through the part data base. The hard-copy documentation for the top and bottom case was done after the molds were completed for production parts.

Because we lacked sufficient experience with single-sided printed circuit boards, manufacturing engineering gave considerable attention to the solderability and testing of the board. Design guidelines were first obtained from Roseville Terminal Division. The pad and trace design incorporates features designed for optimum solderability and strength in the finished product. Solder defect data was collected by conducting wave soldering experiments at Vancouver Division, from which design modifications were determined.

During development, the decision was made to transfer production to Singapore Manufacturing Division. A coordinated effort for a smooth transition was accomplished in several stages. First, assembly tooling was designed and built in Corvallis with the aid of Singapore engineers. Parts were sourced domestically, whether custom or commercially available. Lab prototypes were assembled in Corvallis. The results gave information upon which design improvements, tooling debug, and process refinement were based. Complete QA testing was conducted in Corvallis with a Singapore engineer, while some of the tests were duplicated in Singapore. Singapore then began procuring parts locally and initiated tooling for custom parts except plastic molds. Tooling and custom parts were shipped to Singapore for the production prototype build, for which Corvallis engineers were at hand. Finally, for production, the plastic molds were sent to Singapore.

Acknowledgments

Theresa Gibney conducted solderability experiments, coordinated assembly tooling, and designed the line both in Corvallis and Singapore. She also acted as liaison between the two sites. Marc Baldwin coordinated plastic tooling, texturing, and tool transfer. Other members of John Mitchell's manufacturing team contributed to assembly tooling. Gary Watts and Bill Peters designed the molds for the top case and bottom case. Burl Smith programmed the CNC milling machine. Singapore engineers David Shum and Tan Zing Chiou came to Corvallis to aid assembly tooling, line design, and procurement. Herbert Ting came to conduct product qualification. Other members of Ng Say Ban's manufacturing team contributed to the smooth transfer of production to Singapore. Procurement engineers both in Corvallis and Singapore were essential to the success of protoype builds.

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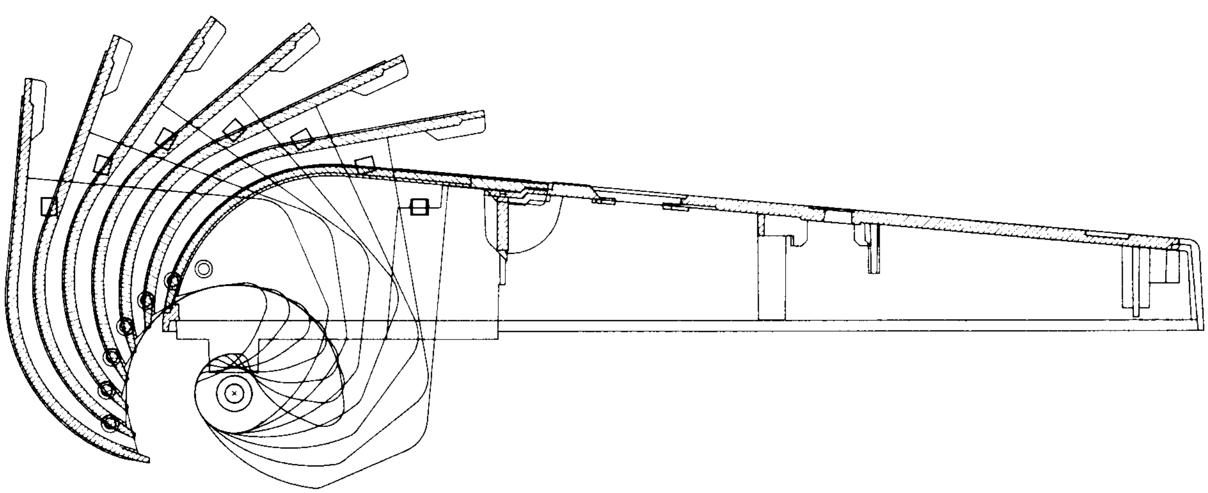

Fig. 3. *Simulation of paper door rotation used to determine the location of its mounting pin.*

Manufacturing State-of-the-Art Handheld Calculators

by Richard W. Riper

HANDHELD CALCULATOR users are demanding more functions in smaller, less-expensive packages. At the same time, new products must be brought out in shorter times. This requires greater cooperation between R&D and manufacturing. On the HP-18C and HP-28C project,[1] the lab and manufacturing teams began working together from the very beginning, long before the mechanical design was firmed up. This helped ensure that the designs coming out of the lab could be built easily on the production line. Also, on this "fast-track" project, much of the tooling work had to begin before all of the design details were worked out.

One form of this cooperation was to have R&D design into manufacturing's strengths—using existing processes and technologies where possible. This meant getting manufacturing personnel involved in the design process, for example by giving the printed circuit board designers guidelines for the size and arrangement of solder pads for the surface mount components and specifying the amount of clearance required for these components for loading. Guidelines for the design of the display assembly were also given so that technologies already developed for the automatic assembly of Series 10 calculator displays could be used.

There were a number of areas of the design, however, that required new manufacturing technologies. A pallet conveyor for final assembly, automated key trim and load, and robotic placement of RTV sealants were new areas for us, and our existing manufacturing capabilities had to be extended in other areas.

One new technology used on this project was CAD/CAM. The HP-18C and HP-28C were the first products at our

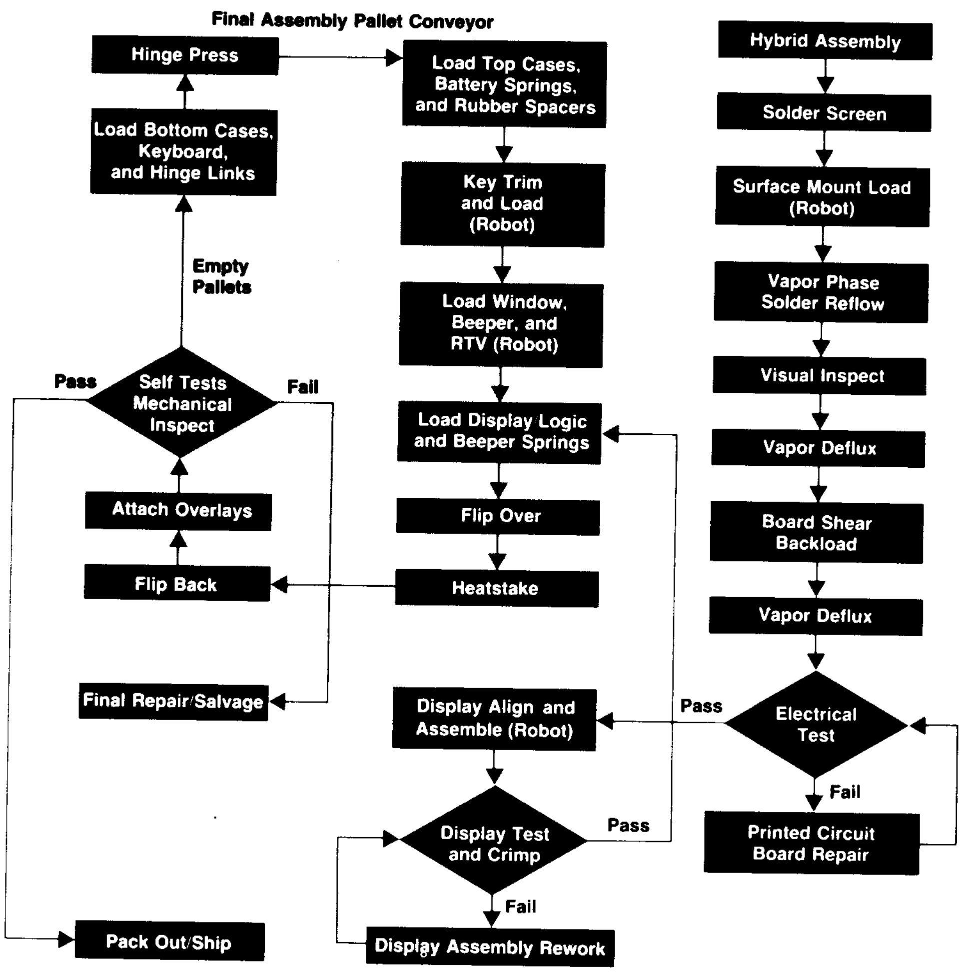

Fig. 1. *Flow chart of the assembly process for the HP-18C and HP-28C handheld calculators.*

division to be designed primarily on our CAD system, which consists of local workstations connected to HP 9000 Computers. This resulted in easier sharing of design information, which also was more accurate. Our CAD/CAM system is linked directly to several computer-controlled milling machines in our model shop, so that parts can be machined without having to reenter part geometry. Some of the tooling was also designed and built using CAD/CAM techniques, which resulted in tools that are more accurate and have better repeatability. Some of the machining on the plastic molds was done using the CAD/CAM system, such as the nomenclature for the keys, saving shop time compared to traditional methods. In addition, the layout of the final assembly line was done on the CAD system, which made it easy to try different alternatives and move assembly stations around for the best work flow.

Production Flow

The production flow (Fig. 1) begins with the electronic assembly. The circuit boards for the HP-18C and HP-28C are produced in a subpanel of four boards to reduce handling of individual boards and to fit the processing equipment. Three custom ICs, the two display drivers and the CPU, are attached and wire-bonded directly to the boards during the hybrid assembly. The panels then move to the printed circuit assembly area for other components. Here the subpanels are screened with solder paste and fixtured in a robot workcell for loading of the surface-mount components (Fig. 2). The robot arm contains a reflective-light sensor, which is used to find the exact position of the etched conductor traces on the subpanels. This ensures that the two ROMs and 12 discrete components are loaded accurately. This is an example of designing into manufacturing's strengths, since similar robots load boards for our established products such as the Series 10 Calculators and the HP-71B Handheld Computer. It is also an extension of our existing capability in that this is the first time we have added surface-mount components to a hybrid circuit.

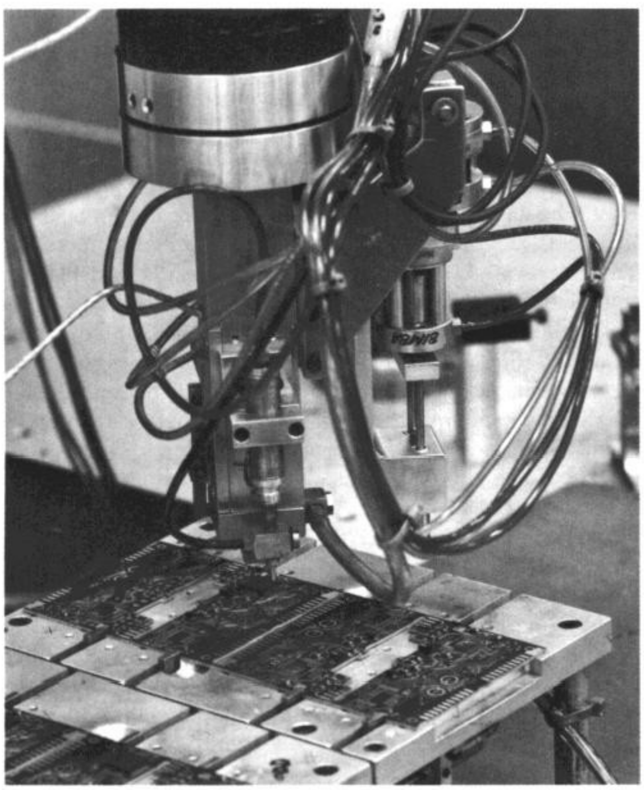

Fig. 2. *SMT robot.*

The HP-18C Business Consultant is produced in five languages: English, French, German, Spanish, and Italian. Currently, the HP-28C is produced as a single-language product. Each HP-18C language variation has its own ROM set so that softkey labels and messages appear in the localized language. The six different printed circuit assembly variations are produced by just changing the ROM set. This greatly reduces the number of subassemblies that must be stocked and reduces the changeover time to build a different model to minutes.

After robot loading, the subpanels enter an automated soldering system. They are fed on a conveyor through a predrying oven to drive off the solvent in the solder paste, then into a vapor phase reflow machine where the balls of solder in the paste liquefy, soldering the components onto the board. The subpanels are then inspected for solder joint quality, washed, and sheared apart into individual boards. Four components not currently available in surface-mount packages are then hand soldered to the boards before they are washed again and sent to electrical test.

The boards are electrically tested on an HP 3065 Board Test System using a fixture that was designed and built just for this product. The test fixture probes both sides of the board simultaneously, including all of the pads for connection to the liquid-crystal display (LCD). This fixture is also used for testing the subpanels during the hybrid assembly, which gets more leverage out of one tooling design. The tested assemblies then move to the final assembly area, where they are mated with the LCD before being placed into the calculator.

Final Assembly Conveyor

The final assembly of the HP-18C and HP-28C represents a departure from the way we have fabricated previous products. Instead of a rigid, one-piece package, the calculator has two main cases connected by a double-jointed hinge. This makes the product hard to hold during manufacturing, especially before all of the parts have been joined together. For this reason, we chose a pallet conveyor for moving the calculator through the assembly steps. Another benefit of using this type of conveyor is that the amount of work in progress (WIP) can be tightly controlled. This leads to better control of inventories and more efficient production.

The pallet conveyor assembly line (Fig. 3) is controlled by an HP Series 9000 Model 236 Computer. This computer is interfaced to the hardware through three HP 3488A Data Acquisition and Control Units and its control software is based on a program written to control a similar conveyor used in the assembly of the HP Vectra Personal Computer.

The pallets (Fig. 4) consist of a metal plate held in a plastic frame by four precision bushings. These bushings allow accurate alignment of the pallets at each of the automated stations on the line. The plates are fixtured to hold the parts of the calculator, with one calculator per pallet.

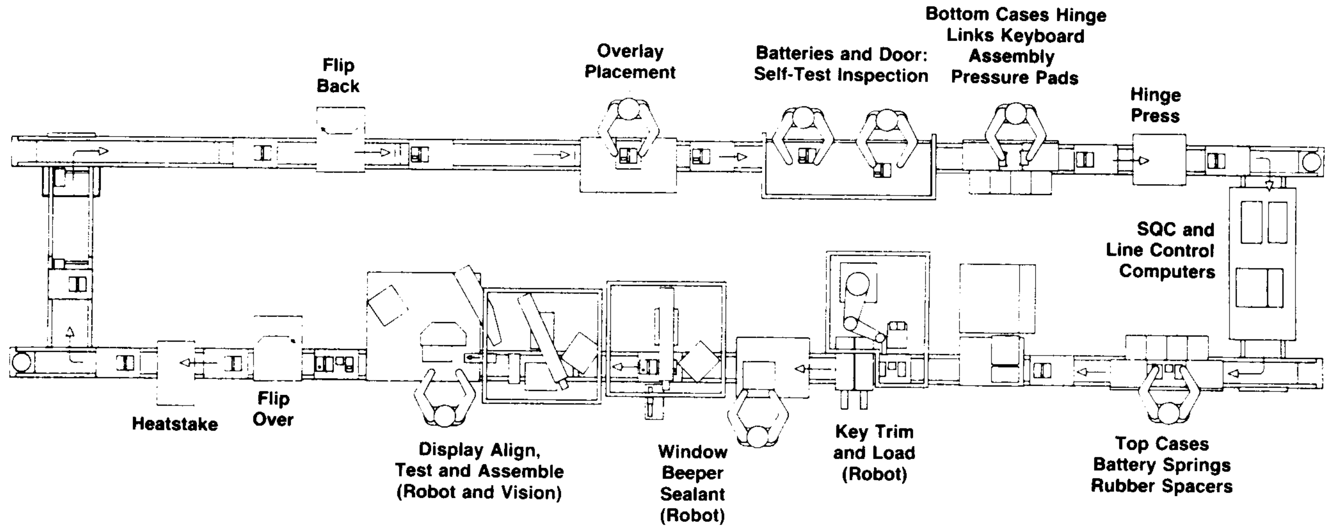

Fig. 3. *Final pallet conveyor assembly line layout.*

Metal plates embedded in the plastic frame of the pallet activate inductive switches mounted on the conveyor so that the control computer will know when the pallets are in position. The computer controls all pallet movement around the rectangular conveyor, signaling the automatic stations to start operation once a pallet is in position. The computer also watches for signals from the operators at the manual stations that they have completed their operations and the pallets can be moved on. The conveyor is asynchronous, so each pallet can move on once an operation is finished as long as there is space available for it downstream. This pallet conveyor then forms a mechanized demand-pull production line.

The first station on the final assembly line is a manual station where an operator places the two bottom cases and the hinge halves on the pallet. The polyester-film keyboard assembly is also placed in the cases and routed through the hollow hinge at this station. The second station is an automated hinge press which completes the snap-together assembly of the hinge halves. After moving across the end of the conveyor, the operator at the third station places the top cases into the pallet after snapping in the battery contacts. These formed wire battery springs give reliable contact to the printed circuit board without the need for hand-soldered wires. Soldered wires not only take a long time to assemble, but are very difficult to automate.

The next station on the assembly line is an automated key trim and load system. The keys are two-shot molded in clusters (the key label is molded from a different color of plastic, not just printed on). These clusters must be trimmed apart, leaving the individual keys. The keys cannot be molded in the same sequence as they appear in the product, as is done in our other calculators. In addition, the keys are molded from three different colors. This required the development of a robotic system capable of taking the trimmed keys and placing them in the proper locations in the top cases.

The controller for this robot has two parallel processors, which allows it to operate the key trim machines at the same time that the robot arm is loading keys onto a fixture that flips them down into the top cases waiting on the pallet. The clusters of keys are stacked in metal magazines after plastic molding, allowing automatic loading of up to 100 calculators without attention from an operator. The five different language variations of the HP-18C use the same set of keys, while the HP-28C uses a different set of clusters. Again, changeover can occur in a few minutes.

At the next station, an alcohol-cure RTV compound is dispensed into the cases by a robot to bond the display window and the piezoelectric beeper. RTV is also used to seal the electronics against damage if the batteries should leak and to provide additional protection against electrostatic discharges. A robot was chosen for this operation because it can apply a smooth, uniform, and continuous bead of RTV, an operation difficult for an operator to do by hand. At this station, as well as at the key-load station before it, the pallet is positioned by the bushings for accuracy. The windows are inspected by an operator for cosmetic defects and placed in a tray that is presented to the robot. The beepers are stack loaded in a magazine and fed automatically to the robot.

The next operation attaches the LCD to the printed circuit assembly (Fig. 5). This operation uses another robotic system, chosen for the high accuracy required. The liquid-crystal displays, as well as the metal clips that hold them to the printed circuit assembly, are tray loaded for the assembly robot. The robot places the clip in a holding fixture and passes the LCD under a reflective-light sensor to find the interconnection pads. The robot then takes the LCD to an automated tape dispenser and places strips of double-sided adhesive tape on each long side of the LCD. The robot then places the LCD into the metal clip, based on the position data sensed earlier. The LCD and clip assembly is then placed on a ramp that slides the assembly to an operator who places two elastomeric connectors over the LCD contact pads and mates the assembly with the hybrid printed circuit board.

The resulting assembly is then placed in a tester/crimper,

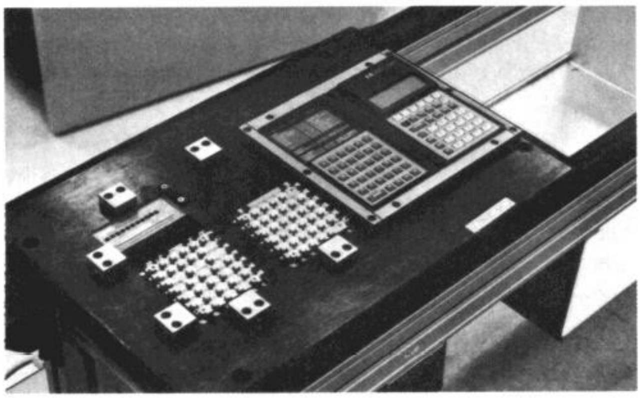

Fig. 4. *Final assembly pallet.*

where the keylines and several test points on the printed circuit board are probed and a set of diagnostic tests is run. A vision system uses two cameras to look at the LCD during this test to make sure that all of the pixels are operating. With over 4,000 pixels per display, this is not an operation that can be reliably done by eye. After the assembly passes the test, the tool automatically folds over the tabs on the metal clip, holding the printed circuit board and the LCD tightly together. The operator places this assembly into the calculator and places two conical beeper springs

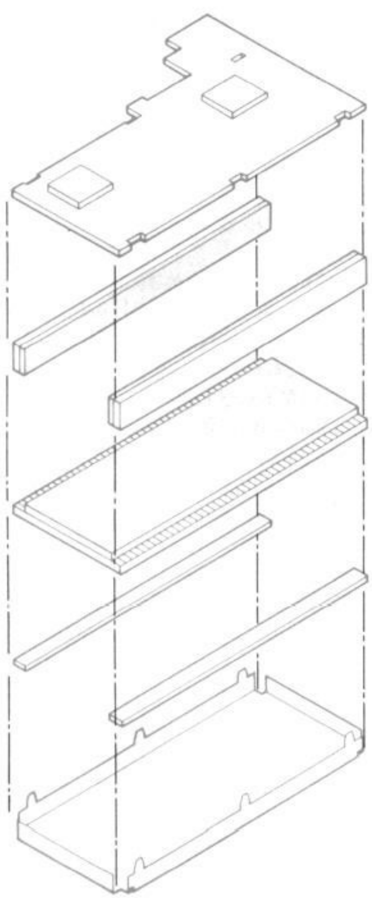

Fig. 5. *Exploded view of display assembly attachment to logic board.*

into holes in the printed circuit board. Like the battery contacts, these give reliable contact without the need for hand-soldered wires.

The pallet then moves to the first of two flip stations, which is an automated tool that picks up the back case assembly and mates it with the top cases. There are 101 plastic bosses molded in the bottom cases that have to fit through holes in the top cases, with little room for misalignment. The next station is an automated heatstaker, which uses heated pins to form rivet-like heads on the plastic bosses. These hold the calculator together—no screws are used. Once heatstaked together, there is no way of getting a unit apart without destroying the plastic cases. After passing across the end of the conveyor, the pallet stops at the second flip station, where the assembled calculator is turned back over into the other side of the pallet.

The next station is a manual station where the overlay labels are placed on the calculator. These four labels cover the heads formed on the plastic heatstake bosses and provide user information. The overlay set is different for each model and language variation being produced, just as the ROM set is. The pallet then passes on to the last station, where the batteries are placed in the calculator and a number of self-tests are run. The calculator is also inspected for cosmetic defects and sample printing is done on the separate printer to make sure that the infrared LED transmitter for sending data to the optional printer operates correctly. The empty pallet continues on the conveyor to the first station to start the cycle all over again. The finished calculators are carted to the pack-out area, where they are boxed with the owner's manual. The owner's manual is another part of the product that is peculiar to the model and language.

Acknowledgments

The other members of the manufacturing engineering team that worked on this project included Dirk Bodily, George Custer, Ken Frazier, Jerry Hackett, Horst Irmscher, John Liljeberg, Martin Marino, Ralph Sebers, and Bob Walsh. The final assembly line controller was developed by Bob Clark, Roger Quick, Kathy Shelby, and Carl Johnson. A great number of people in tool build, the model and NC shops, and elsewhere contributed a lot of time and effort to getting the tools ready on time. A special thanks to the production workers on the HP-18C and HP-28C, especially those who were involved from the earliest prototype builds.

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A second and related issue is to demonstrate the utility of students having their own personal computers, versus making available a smaller number of computers located in central teaching areas, a dormitory common room, and the library. We will explore this alternative approach in the next few years as we respond to a legitimate concern on the part of a growing number of students who are not in the New Pathway program, but who want equal access to the benefits of the information technology.

We are also concerned with the extent to which the information technology developments can and will be adopted by other medical schools. Obviously, if the technology innovation is successful, it would be foolish to expect that each of the 170 different medical schools should develop its own program and its own software. However, we do not know yet to what extent programs developed by our faculty for our students and for our educational environment will be acceptable to other faculties in other educational environments. We hope to address this question in the next two years by initiating a collaboration with several other medical schools whose educational objectives are similar.

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Authors

October 1987

4 — In-Service TIMS

Norman Carder

Norman Carder is a senior development engineer with HP's Queensferry Telecommunications Division. A native of Belfast, he received his BSc degree in electrical engineering and electronics from Queens University in 1978. He joined HP the same year, and has contributed to the design of high-speed modems, the HP 3764A Transmission Analyzer, and the HP 4948A ITIMS. His work on the HP 4948A resulted in a patent application. In 1984 he received an MSc degree in digital techniques from Heriot-Watt University. Now a resident of South Queensferry, Scotland, Norman is married, plays bass guitar, and enjoys camping, walking, and skiing.

William I. Dunn

Ian Dunn joined HP in 1984 with a background in superconductivity research, marine research, and electronic consulting. He has published papers on quantitative sonar techniques and a paper on energy dissipation in superconductors, and is named coinventor in a sonar-related patent application. He contributed to the control processor firmware design for the HP 4948A ITIMS. A native of Glasgow, he holds a BSc degree in electrical engineering from Glasgow University. Ian lives in Kinross, Scotland, is married, has three children, and is involved in politics. To relax, he favors mountaineering, skiing, photography, gardening, cooking, and taking his trailer to the Scottish Highlands or the continent.

David W. Grieve

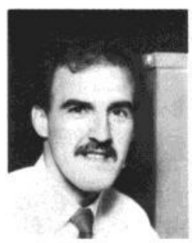
David Grieve is a senior design engineer with HP's Queensferry Telecommunications Division, and has contributed to the design of the HP 37212A Modem and the HP 4948A ITIMS. He received his BSc degree in electronic engineering from the University of Manchester Institute of Science and Technology in 1979 and joined HP the same year. Born in Cuckfield, Sussex, England, David now lives in Edinburgh, and has made learning to speak Chinese one of his goals. He's married, and he and his wife are expecting their first child soon.

James H. Elliott

Jim Elliott is a specialist in microprocessor hardware and firmware design. He received his BSc degree in electronic engineering from Edinburgh University in 1982 and his MSc in digital techniques from Heriot-Watt University in 1986. A design engineer with HP's Queensferry Telecommunications Division since 1982, he contributed to the design of the HP 4948A ITIMS. Jim was born in Dunfermline, Scotland, and now lives in Edinburgh. He plays badminton, has a blue belt in karate, and likes to travel.

W. Gordon Rhind

4948/Elliott



Gordon Rhind received his BSc degree in electrical engineering in 1969 and his PhD in digital telemetry in 1972, both from Edinburgh University. He joined HP's Queensferry Telecommunications Division in 1979 with experience in the design of inertial navigation systems. He's been a senior design engineer for high-speed modems, was project manager for the HP 4948A ITIMS, and is now a section manager. A member of the IEE, he's the author of a paper on applications of inertial systems to land survey and is named a coinventor in a patent application on the HP 4948A. Gordon was born in Armadale, West Lothian, Scotland and lives in Linlithgow, West Lothian. He's married, has two sons, and has been known to participate in running, squash, and golf. He's also a connoisseur of "real" ales.

16 — Infrared Link

Robert S. Worsley

With HP since 1977, Bob Worsley has contributed to the design of a number of calculator and printer products. His past projects include the HP-41CX Calculator, HP 82143A Printer, HP 82240A Thermal Printer, and the HP-18C. Bob was born in Stamford, Connecticut and is a graduate of San Jose State University (BSEE 1977) and Oregon State University (MSEE 1982). He lives in Corvallis, Oregon, is active in his church, and likes hiking, cross-country skiing, and gardening.

Bruce A. Stephens

With HP since 1979, Bruce Stephens is an R&D engineer in the Handheld Computer and Calculator Operation. His first HP project was the HP-71B Computer and he worked on the hardware interface for the HP-18C and HP-28C Calculators. In addition to designing and developing calculators, he has played a major role in creating firmware development tools. Born in southern California, Bruce holds a 1979 BS degree in computer science from the University of California at Irvine. He's an avid runner and enjoys skiing, bicycling, birdwatching, and listening to all kinds of music.

Steven L. Harper

Steve Harper came to HP in 1972, the same year he graduated from Brigham Young University with an MSEE degree. He has worked on software for the HP 9551D Instrument Calibration System and on calculator microprocessor design for the HP-71B Computer and has been a project manager for HP-IL interface products. Most recently he contributed to the development of the HP 82240A Thermal Printer. He has written several articles on HP-IL, including two in the *HP Journal* (January 1983), and is coauthor of a book on the same subject. An Oregon native, Steve was born in Medford. He and his wife and five children currently live in Corvallis. He's active in his church and likes boardsailing, camping, softball, and tennis.

21 — Portable Printer

Masahiko Muranami

Born in Tokyo, Japan, Jack Muranami earned his BSME degree from Rice University in 1985. He joined HP the same year and was a member of the R&D design team for the HP 82240A Thermal Printer. His speciality is the design of plastic and metal parts. Jack is married, has a young son, and lives in Corvallis, Oregon. His pastimes include gardening, cooking, and playing with his son.

David L. Smith

With HP since 1982, Dave Smith is a specialist in plastic part design. He has designed parts for the HP-71B Computer, HP-18C Calculator, HP 82240A Thermal Printer, and HP-94 Computer peripherals. He holds a 1982 BSME degree from California Polytechnic State University at San Luis Obispo. An Oregon native, he was born in Klamath Falls and now lives in Corvallis. He's married and is building a house this summer with the help of his family. His other interests center around outdoor sports, especially skiing and running.

24 — Calculator Manufacturing

Richard W. Riper

With HP since 1982, Rick Riper coordinated manufacturing engineering for the HP-18C and HP-28C Calculators. Earlier, he was a manufacturing engineer for HP-10 Series Calculators and the HP-75D Computer. He also worked on a cost-reduction project for the HP 82161A Cassette Drive and on the HP 82162A Printer. Rick was born in Chester, Pennsylvania and is a 1982 graduate of Oregon State University (BSME). He's a certified professional engineer in the State of Oregon. A resident of Corvallis, Oregon, he's married and has two children. His outside interests include bicycling and photography.

28 — New Pathway Curriculum

G. Octo Barnett

Octo Barnett was born in San Diego, California and earned a BA degree in chemistry at Vanderbilt University (1952) before completing work for his MD degree from Harvard University in 1956. He is a professor of medicine at Harvard Medical School and director of the Laboratory of Computer Science at Massachusetts General Hospital. Early in his career he served in the U.S. Public Health Service and was an established investigator for the American Heart Association. Later he specialized in medical information systems, medical informatics, and computer-based medical education. He has published over 100 papers in the field of medical informatics and is a member of several professional societies. Now a resident of Newton, Massachusetts, Octo is married and has three children, one of whom works for HP. For recreation he enjoys windsurfing, cross-country skiing, tennis, wilderness camping, and canoeing.

Gordon T. Moore

Gordon Moore received his undergraduate education and medical training from Harvard University and completed work for his MD degree in 1963. He served in the U.S. Public Health Service and later became chief operating officer and medical director for the Harvard Community Health Plan. He's now director of the New Pathway Project for Harvard Medical School. His publications include over 20 articles and papers in the fields of health services research and medical education. Born in Buffalo, New York, Gordon is a resident of Cambridge, Massachusetts. He's married and has two children and enjoys piano and sailing.

Judith L. Piggins

Judy Piggins holds BSEE and MSEE degrees from the Massachusetts Institute of Technology (both awarded in 1973) and an EdM degree in counseling and consulting psychology from Harvard University (1979). She designed and implemented medical software for Hewlett-Packard from 1973 to 1978 and has taught mathematics and computer science. She now manages the New Pathway Project for Harvard Medical School. She is author or coauthor of 13 papers on medical informatics and specializes in medical education and computerized medical record systems. Judy was born in Detroit, Michigan and lives in Watertown, Massachusetts. Scuba diving, hiking, aerobics, reading, and travel are her favorite leisure activities.

Ethan A. Foster

Ethan Foster is a Massachusetts native with a BS degree in computer science from Worcester Polytechnic Institute (1981). He spent three years as a programmer/analyst for medical data base systems at Massachusetts General Hospital before becoming lead programmer/analyst for the Harvard New Pathway Project. Ethan was born in Greenfield and he and his wife now live in Haverhill. He enjoys canoeing, camping, and skiing.

37 — Program Development

Robin M. Gallimore

Robin Gallimore is software engineering department manager at the HP Laboratories Bristol Research Centre. With HP since 1985, he has also served as project manager for rigorous system specification and design. Before joining HP, he was a university lecturer in computation at the University of Manchester Institute of Science and Technology. He has published several papers on formal methods in software engineering, and is a member of the British Computer Society special interest group on formal aspects of computer science. He graduated from the University of Manchester Institute of Science and Technology with a BSc degree in computation in 1971. Robin is married and has a baby son. His interests include photography, jazz, and playing classical guitar.

Derek Coleman

Derek Coleman is a project manager at HP's Bristol Research Centre, working on tools to support rigorous software development using formal specification. Before coming to HP in 1985, he was a university lecturer at the University of Manchester Institute of Science and Technology and a visiting professor at the University of California at Berkeley. A member of the British Computer Society and a committee member of the special interest group on formal aspects of computing, he has published several papers on software engineering and a book on structured programming. He received his BSc degree in physics in 1965 and his MSc in computer science in 1970 from the University of London.