

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 Calculators² 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 interface⁵ 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

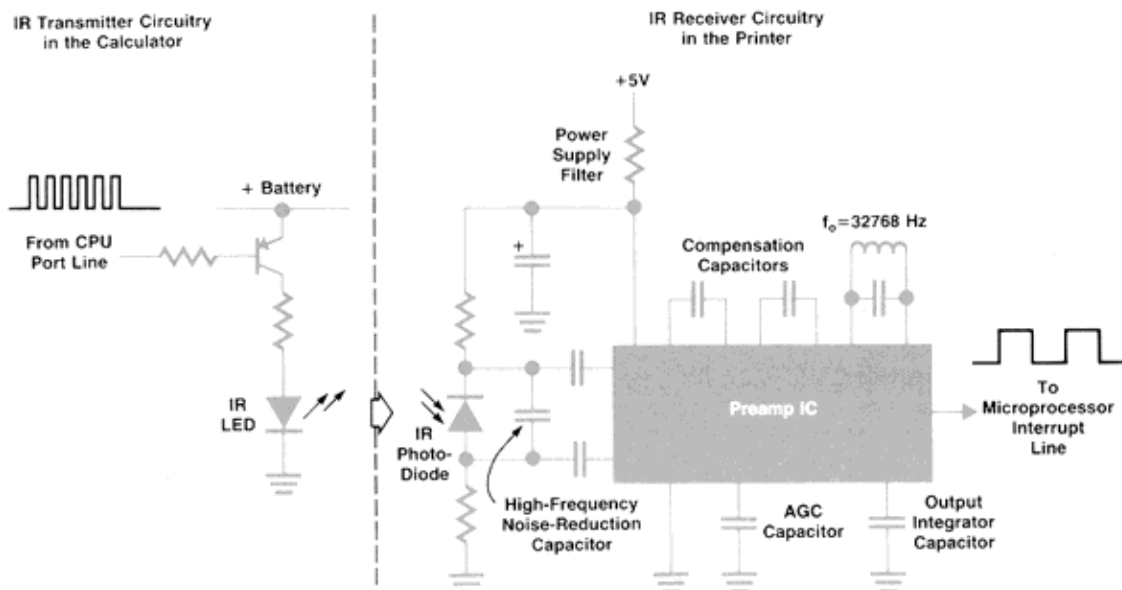


Fig. 1. Infrared link schematic diagram.

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- μ s pulse of light followed by a 15.26- μ s pause.

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 μ s). 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:



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.

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 ($1 \rightarrow 0$ or $0 \rightarrow 1$) 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.

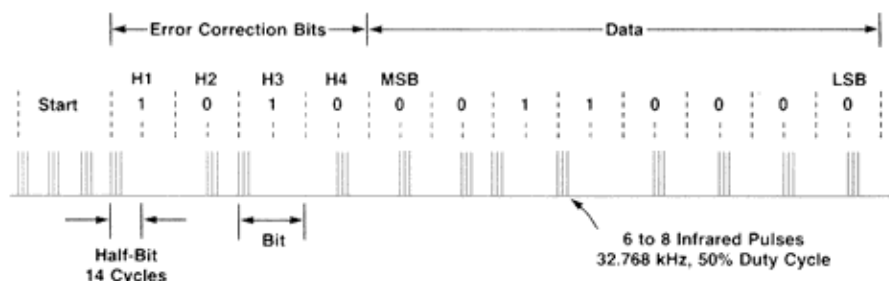


Fig. 3. Example of infrared message frame.

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- μ s 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- μ s-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 n th 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 μ s too long. Similarly, the output could go true on the $(n+1)$ th pulse in one burst and on the n th pulse in the next burst, which would make the interval look 30.5 μ s too short. Therefore the error from the preamplifier is approximately $\pm 30.5 \mu$ s.
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 μ s). 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 μ s), 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.

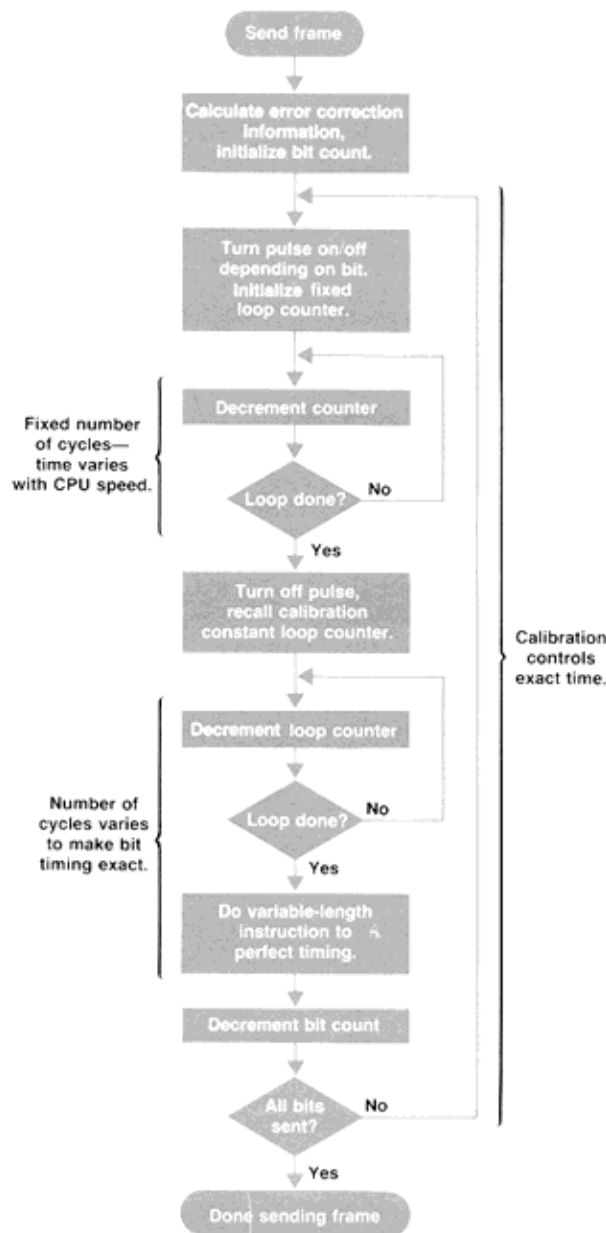


Fig. 4. Flowchart of algorithm used by calculator to adjust data transmission timing.

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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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

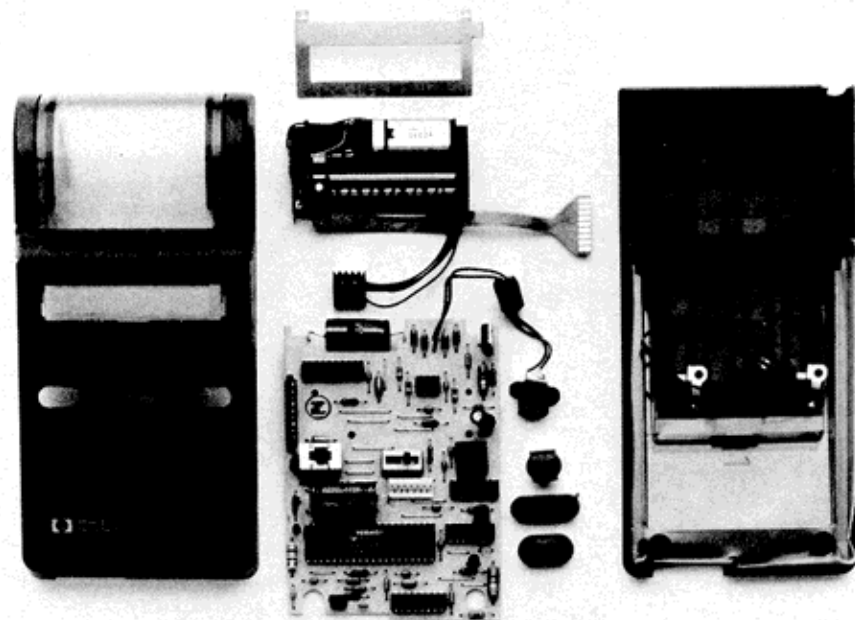


Fig. 2. Components used in HP 82240A.

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 commer-

cially 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 prototype builds.

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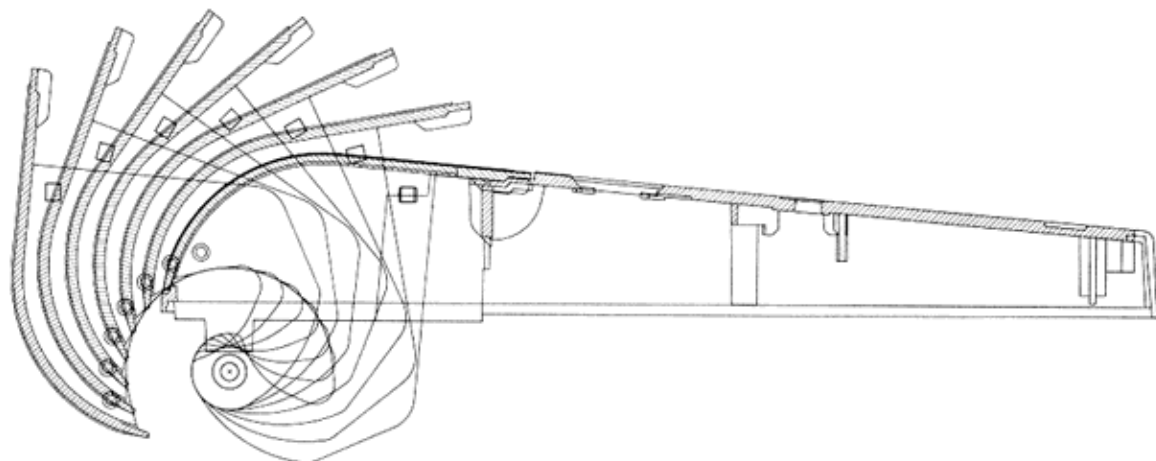


Fig. 3. Simulation of paper door rotation used to determine the location of its mounting pin.

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

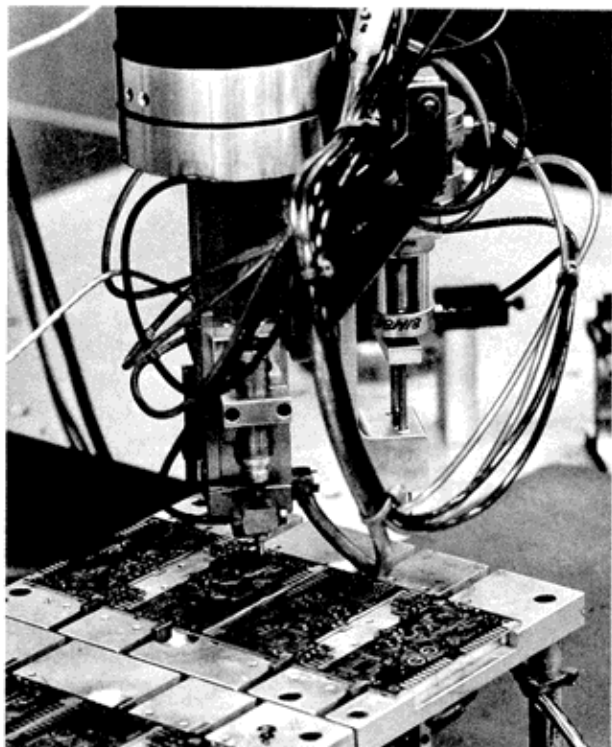


Fig. 2. SMT robot.

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.

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.

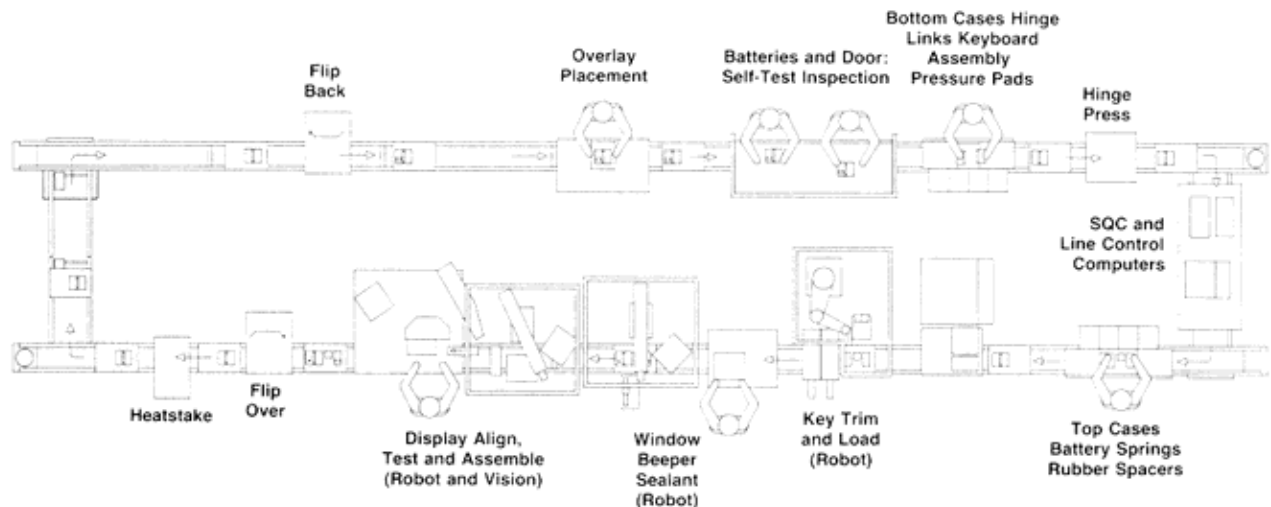


Fig. 3. Final pallet conveyor assembly line layout.

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,

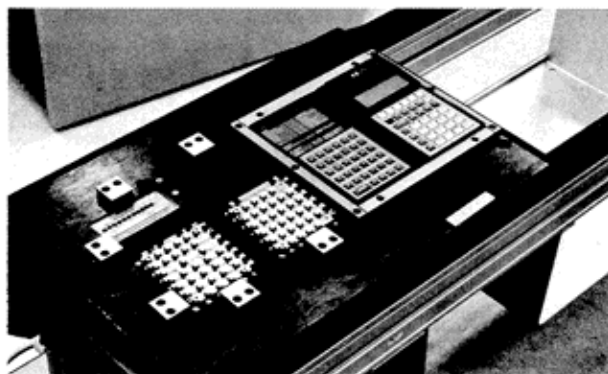


Fig. 4. Final assembly pallet.

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

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.

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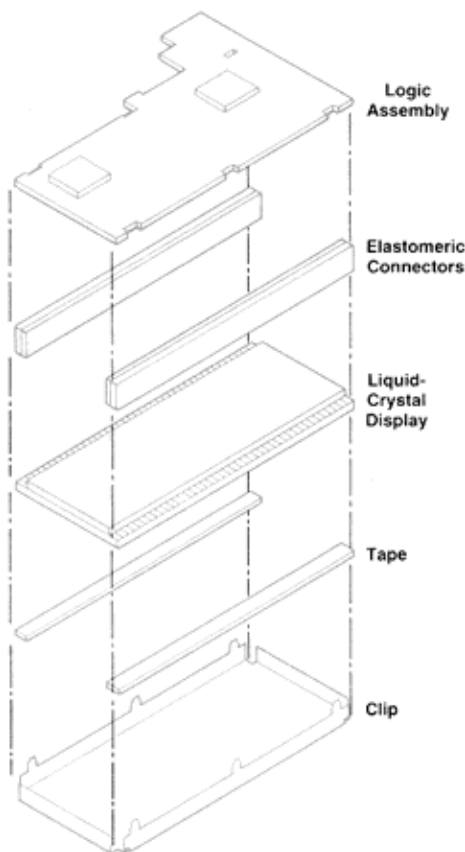


Fig. 5. Exploded view of display assembly attachment to logic board.

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