its calculated value, and the equation that was solved to find it, in the order that the unknowns were determined by the solution procedure.

Acknowledgments

I would like to thank the rest of the development team and the people who made exceptional contributions to the product: Jim Donnelly and Megha Shyam for making it all happen, Dennis York for the initial vision, Lynn Winter for a catalog engine that was an enduring foundation, Chris Bunsen for critical design advice and testing for the Multiple Equation Solver, Diana Byrne for spearheading the software testing effort, Hank Schroeder for an owner's manual in a remarkably short time, and Ray Depew, whose thoroughness testing the Periodic Table was critical to both the card and the HP 48SX.

Hardware Design of the HP 48SX Scientific Expandable Calculator

Leveraging an earlier design resulted in prototypes with 90% production tooled parts only nine months after the start of the project. The HP 48SX includes an 8-line-by-22-character super-twisted nematic liquid crystal display, two expansion ports for ROM or battery-backed RAM cards, and two I/O ports: RS-232 and infrared.

by Mark A. Smith, Lester S. Moore, Preston D. Brown, James P. Dickie, David L. Smith, Thomas B. Lindberg, and M. Jack Muranami

THE NEEDS OF HP HANDHELD CALCULATOR customers—engineering, math, and science students and business and scientific professionals—have radically changed over the years, as the personal computer has become the standard tool of technical students and professionals. However, the need for convenient, handheld computation has not disappeared, but simply evolved.

Surveys of our high-end technical calculator customers reveal that nearly all own or have access to a personal computer, that they use their calculator daily, that professionals make up about half of the customers for high-end technical calculators, and that they need a powerful handheld calculator with graphics and I/O capabilities. The HP 48SX scientific expandable calculator (see Fig. 1 on page 6) is designed to meet their needs for more advanced computation, graphics, customizability, expandability, and the ability to link to their personal computers.

The 64-row-by-131-column STN LCD (super-twisted nematic liquid crystal display) provides the means for presenting the power of HP 48SX graphics, matrix manipulations, and equation entry. Two plug-in card slots provide RAM expansion (in 32K-byte or 128K-byte increments) and customization (plug-in application ROMs such as HP's Equation Library ROM card described in the article on page 22). A serial I/O port provides a means to link to an IBM PC-compatible or Apple Macintosh computer, and an IR (infrared) port allows sharing of solutions between HP 48SX calculators and provides a link to the HP 82440B infrared printer.

Previous Series Leveraged

One of the primary project objectives for the HP 48SX was extensive leverage from the design and manufacturing

Fig. 1. *Two expansion ports accept ROM or battery-backed RAM cards.*

development of our current calculator family to minimize development time and cost. Design leverage was a primary consideration in every HP 48SX part design. This emphasis on design leverage resulted in laboratory prototype units built with 90% production tooled parts only nine months after the start of the project.

The HP 48SX is a direct descendant of the series of low-cost, high-volume, vertical-format calculators introduced in January 1988. This series, consisting of the HP 10, 14, 17, 20, 21, 22, 27, 32, and 42 calculators, achieved low cost and minimal part count through the use of a few highly integrated designs. These calculators were designed from the outset to be built on a highly automated assembly line at a rate of several calculators per minute.

The designers of the HP 48SX leveraged many of the processes, materials, and even design details from the previous series. As a result, the HP 48SX is able to enjoy the benefits of an automated assembly line that could not have been justified by HP 48SX volume alone (see article, page 40). Sixteen out of seventeen major assembly processes are common to both product lines. Only four parts are shared, but all raw materials and many suppliers are common to both families. A subtle benefit resulted from leveraging design details, since many design decisions were preordained, saving time during the investigation phase. By sharing details, the HP 48SX designers were able to proceed more confidently, capitalizing on the knowledge gained and improvements made as the earlier series of products entered production.

It took some time for the designers to accept leveraging completely, because they were forced to compromise what they envisioned as optimum. Once the commitment was made, however, many unknowns were eliminated and it became clear that, in this case, leveraging was the right way to meet the product and division objectives.

Design Features

The topcase of the HP 48SX is a four-color, injection molded part. Its 49 keys are an integral part of the topcase; each key is attached and guided by two small cantilevers. This design yields a low-profile key with an excellent controlled feel. The keyboard is made of Mylar with tuned-resistance carbon graphite traces. This allows a low profile, reduces cost, and improves reliability because of the inertness of graphite. The battery contacts are engineered to eliminate fretting corrosion and the loss of memory that would inevitably result. The liquid crystal display is a super-twisted nematic (STN) design for improved contrast and viewing angle. Two expansion ports accept ROM or battery-backed RAM cards (Fig. 1). These cards are conveniently sized to be handled easily and have a thin outline.

Throughout the machine, from the generous radius of the bottom case that allows it to fit comfortably in the hand, to the seven small openings in the battery compartment that pick off electrostatic discharges, details are incorporated into the design of the HP 48SX to achieve small size, reliability, and overall customer satisfaction.

Initial Design

Leveraging the design from the previous calculator design resulted in less than optimal tooling and design options.

For the simpler products, the layout of the single display driver IC on the opposite side of the printed circuit board from the display made sense. When applied to the HP 48SX, this constraint forced the 202 outputs from three display drivers to feed through to the display side of the printed circuit board. This wasted a large amount of board area and caused the printed circuit board to be the most expensive non-IC component in the product.

Initially, the mechanical layout was done around the same small button cell batteries that were used in the previous series of calculators. However, electrical system simulations done early in the design cycle showed battery life to be unacceptable and the HP 48SX was redesigned around higher-capacity AAA batteries.

Several other iterations occurred. A printed display window was thrown out in favor of a special hard polarizer optically bonded to the top surface of the LCD. This reduced cost, eliminated the window, which is easily scratched, and resolved a long-standing problem of particles trapped between the window and display. The biggest benefit of the windowless design is the 67% reduction in glare.

For a time we considered incorporating only one plug-in port. The two-port design was eventually selected to allow both ROM and RAM cards to be plugged in at the same time.

Final Design

The HP 48SX is manufactured from three subassemblies: the topcase, the printed circuit assembly, and the bottom case. These assemblies are built from 24 mechanical parts, four surface mount ICs, a 170-pin TAB (tape automated bonding) IC, five discrete leaded components, and 31 surface mount devices (see Fig. 2).

Topcase Assembly

The topcase assembly is designed to be as free as possible of product-specific detail. This was done to allow the basic topcase assembly to be incorporated into future products.

The top surface of the product consists primarily of a 0.012-inch-thick, seven-color, printed aluminum overlay. The purpose of the overlay is threefold: (1) to provide a pleasing surface finish and shape, (2) to carry the nomenclature for three shifted functions as well as the product name and number, and (3) to make the overlay the first line of defense in a carefully designed ESD (electrostatic discharge) protection system. Adding to the cosmetic appearance is an electroformed copper logo which, along with the overlay, is applied to the topcase using pressure-sensitive adhesive.

The four-color molded topcase design represents a major engineering and process achievement. The HP 48SX key nomenclature is actually a separate molded part for each key around which the topcase is shot (see Fig. 3). To create the cavities that form the nomenclature, the legend artwork was digitized on a CAD/CAM system. Cutter paths are generated from this data. The cutter paths are used to cut a positive image of the nomenclature in a carbon electrode. The cutters used are special ground cutters as small as 0.001 inch in diameter at the tip. The electrodes are used for electrodischarge machining of the extremely fine detail into the first-shot cavities. The tolerances must be carefully

Industrial Design of the HP 48SX Calculator

The expressed needs and wants of high-end technical calculator users contributed to the design objectives for the HP 48SX scientific expandable calculator. Needs analysis and concept testing were conducted at the onset of the HP 48SX program, and stated requirements included:

- Handheld product shape (traditional vertical format)
- Large display (8-line desirable)
- Customizable and expandable through plug-in media
- Data I/O for mass storage, printing, programming, etc.
- High-quality tactile keyboard.

In addition to these stated requirements, the industrial design objectives for the HP 48SX included:

- Easily learned accessibility to functions and features through an organized keyboard and display interface
- Direct and easy access to expansion and customization media
- A visual and tactile experience consistent with the product's "next-generation" technological leadership.

Package Design

A softened, vertical-format package allows comfortable handheld use of the HP 48SX. Even the molded rubber feet are sculpted to match the case contour for minimal tactile intrusion. Overall size was determined by the handheld requirement for width, keyboard and display size for length, and component sizes for thickness. Components are located to allow a low leading edge for the keyboard, resulting in a three-degree wedge profile. The keys and keyshapes are leveraged from the previous series of low-cost, high-volume calculators. They are designed to provide comfortable yet positive tactile response, minimal entry errors, and high reliability. User access to batteries and plug-in media is provided through covers at the back of the calculator. Both the infrared and RS-232 I/O ports are at the back, directed away from the user. A molded arrow-shape indicator on the topcase, above the logo, communicates the position of the direction-sensitive infrared I/O feature, and the lens area of the cover over the infrared components is polished to communicate its light-transmissive function. Next to it is the RS-232 port, which accepts a small, custom 4-pin plug designed to match the visual theme and scale of the HP 48SX.

The goal of customization and expansion is accomplished through two plug-in slots for credit-card-size memory modules, available as RAM or ROM applications. The slots are located under a removable cover and infrared lens at the rear of the bottom case. Because of cost and size constraints, an eject mechanism was not feasible for user removal of the cards. Instead, user access is provided by offset-stacking the cards to expose custom, molded plastic grips, which are attached to the cards by the vendor (see Fig. 1 on page 25). These contoured, textured grips are molded with a hole in the center to provide visual access to a title graphic on the printed card surface while the card is inserted in the calculator. The constructed grip texture is consistent in scale and appearance with other grip textures used on the HP 48SX, and enables the user to remove the cards from their friction-fit edge connectors with a single finger or thumb.

A custom soft case was designed to be included with the HP 48SX. Its objectives are to protect the product in normal transport, to provide storage for a quick-reference guide and additional memory cards, and to reinforce the message of product superiority and quality. The final design is a fine-weave pouch. The case is lined and padded, and has a zipper closure. An internal pocket is provided for the quick reference guide and memory cards.

(continued on page 28)

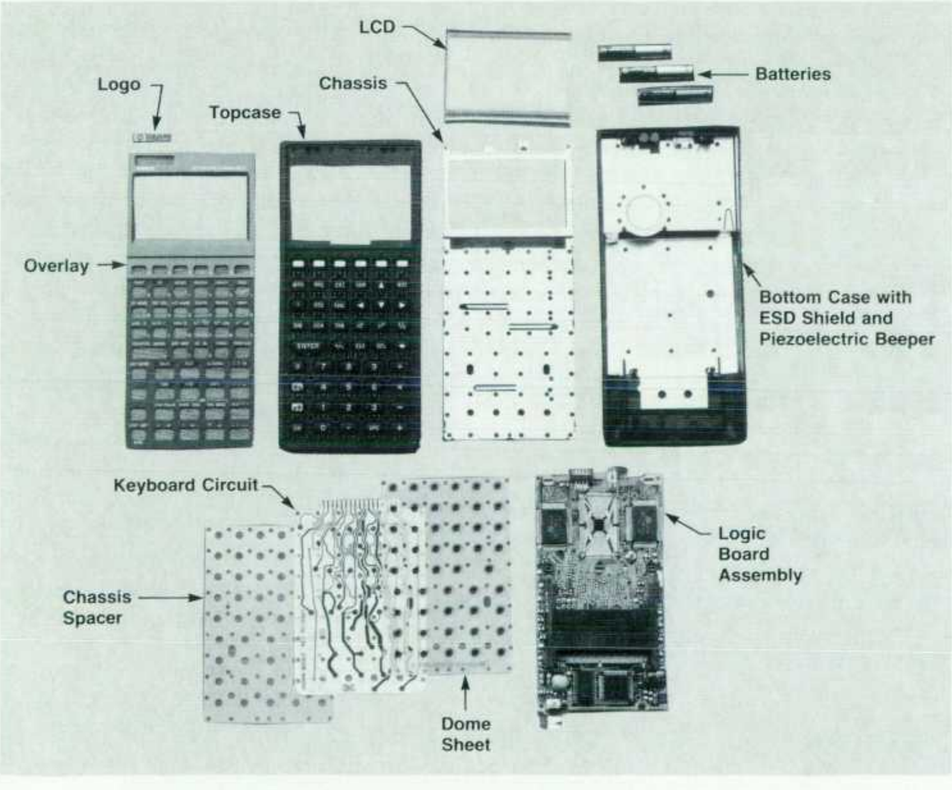

Fig. 2. *The three HP 48SX subassemblies are the topcase, the printed circuit assembly, and the bottom case. They are built from 24 mechanical parts and various ICs, discrete components, and surface mount devices.*

User Interface Hardware Design

Although the HP 48SX approaches computer power and sophistication, it operates primarily as an application with a dedicated keyboard and display interface. The most significant industrial design challenge was to provide visually ordered access to the 2100 functions using only forty-nine keys plus display menus.

The user interface surface of the HP 48SX is divided into two primary zones: the display and display bezel and the keyboard and keyboard overlay (see Fig. 1 on page 6). The windowless 8-line liquid crystal display is framed by a formed aluminum overlay, which "cascades" down to the keyboard in two steps. Located in the middle step is a row of six keys which operate in conjunction with menus presented on the bottom row of the display. The overlay color surrounding these keys is the same as the display bezel to reinforce the association of keys with display menus. The six menu keys are differentiated in size and color from all other keys to distinguish them as special. At the base of the second overlay cascade is the remainder of the keyboard, which provides quick, direct access to alphanumeric entry, math operations, cursor control, and function sets presented as display menus. The total of 49 keys was chosen based on the minimum number required to provide discrete alphanumeric entry. Keys are grouped and sized according to function and relative frequency of use to order the keyboard visually.

The majority of the function markings are printed on the aluminum overlay. Unlike preceding models, including the HP 41C, there was no opportunity to place a second set of function markings on the keys. This is because of the leveraged keyboard design, which is limited to a single, integrally molded function marking. This presented a graphic challenge because the keys access up to four major functions each. As a result, the keyboard overlay is designed with up to two shifted functions above each key, positioned side by side and accessed by color-coded shift keys. The shift keys are also coded with arrows indicating left or right for the relative position of the shifted nomenclature. These symbols are used in the documentation in place of color to reduce printing costs. Twenty-six keys also have an alpha character at the lower right corner, accessed by an alpha shift key. Shifted functions that call up screen menus are distinguished by a black field behind the text and are grouped in two areas of the keyboard. The overlay has a total of six silk-screened colors and one tint. The keyboard is designed to accept snap-in custom overlays for user-programmed keys, custom application requirements, and so on.

Colors

A very dark, high-chroma brown called mercedes black was chosen for the two major case parts for its consistency with the new calculator line and strong customer preference in earlier appearance tests. Because of the integral design of the hinged keys, they share the case color. A warm gray metallic color is used on the display bezel to feature the display area visually, soften the transition to the liquid crystal display, and add richness to the overall product appearance. The background color of the keyboard overlay is a lighter version of mercedes black called mercedes medium, which provides a subtle contrast to give the keys visual prominence.

The most challenging colors to determine were the light blue and coral shift colors on the keyboard overlay. The shift colors on all HP calculators are intended to contribute an accent color on otherwise neutral platforms, and to code the product visually into a product category (business, scientific, or RPN scientific). The HP 48SX is in the scientific category, but functions in both algebraic and RPN modes and is really in a category of its own. The two shift colors selected were originally used for the two scientific categories, but are lightened for readability. In addition to their both being "scientific" colors, they were selected because of their easily distinguishable hues and their balanced values and chroma, which help alleviate a spotty appearance. All other function markings are in legend light gray, selected for its neutrality and readability on the background colors.

Corporate identity is provided by a nickel-plated electroformed logo, selected for its high-quality, three-dimensional appearance. The product name is designed for consistency in location and fonts with other current HP calculators, and is printed in a nickel metal tint to match the logo.

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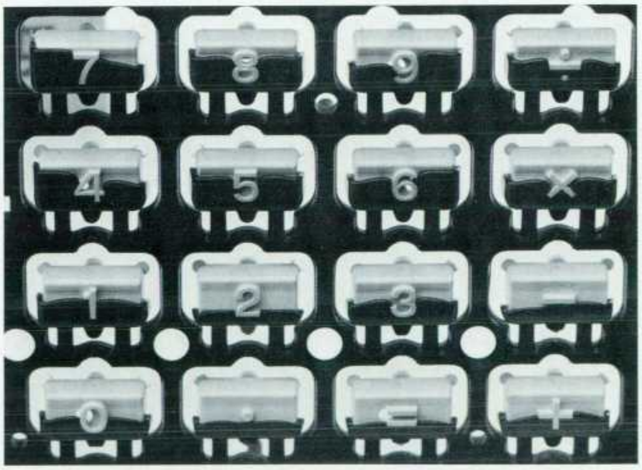

Fig. 3. *A "short-shot" photo of the HP 48SX keys. A separate molded part for each key produces the key nomenclature. The topcase is molded around the key nomenclature. Notice the hole in the* **9** *key, which is formed by a moving core pin. This hole allows the second-shot plastic (dark) to flow into the center of the 9.*

controlled because the curved steel surface of the second-shot cavity must "shut off" against the corresponding curved plastic nomenclature that was formed in the first-shot cavity. The raised-plastic nomenclature ribs must be just touched by the second-shot cavity. The interference between the two must be large enough to prevent the nomenclature from being pushed around by the injection pressure of the second-shot plastic but not so large that the nomenclature plastic is crushed and distorted by the clamping force, which can be as high as 400 tons.

The 49 keys are integrated into the topcase design to simplify assembly and eliminate the possibility of misloading a key. To achieve good tactile feel, each key is suspended on two cantilevers, each 0.016 inch thick by 0.116 inch long. These small beams serve three purposes. They guide the key through a well-controlled arc, they permanently attach the keytops to the topcase, and they serve as the paths through which the second-shot plastic flows. To fill the keytops through these small beams, each key has its own gate, for a total of 60 gates. An ordinary part of this size would have only one gate.

The Triax material used for the topcase is a Nylon-ABS alloy and was specifically selected for its toughness and processing characteristics. The most critical aspect of the topcase design is the small cantilever beams. The beams had to be tough enough to maintain their mechanical integrity through environmental and life testing, yet supple enough not to degrade the force-deflection characteristics engineered into the snap domes. The Triax plastic was found to flow well, which allows a thin beam, and its toughness was verified in testing over 2.5 million key cycles without failure.

The tactile feel of the keys is a result of painstaking design, testing, and quality assurance efforts. The 0.004-inch-thick Mylar dome sheet contains 49 details, which provide the snap feel as each key is depressed. Each key has an actuator which presses against the top center of the dome. As the dome is pressed it deflects at its base into a dome spacer recess. At this stage the force is building linearly with deflection. As the force builds to the trip point the dome buckles, causing a sudden drop in force. Momentum and the resulting imbalance of force between the finger pushing on the key and the key no longer pushing back causes the inside of the dome to impact firmly against the keyboard contacts. The inside of the dome is printed with a pad of conductive carbon graphite. Upon switch closure the dome pad shorts the interdigitated carbon graphite contact fingers of the keyboard. Below each key switch is another recess created by a 0.003-inch-thick chassis spacer. This recess allows the keyboard to wrap around the depressed dome, resulting in a much more reliable area contact instead of the point contact of a dome against a flat plane.

The keyboard is a 0.003-inch-thick Mylar sheet with screen-printed carbon graphite traces and contacts. The feedthroughs of the two-layer keyboard employ triple redundancy to improve yield and reliability. The keyboard lines are multiplexed with the address lines. This scheme reduces the pin count on the IC and saves printed circuit board area, both of which lower costs. However, it requires that key line resistance be carefully controlled. The exact sheet resistance of the carbon ink was measured. This information was used to hand-tune the area of each of the 98 key line traces.

The backbone of the HP 48SX is the nickel-plated 0.018-inch-thick stainless steel chassis. The chassis serves several functions, the most obvious of which is to support the keyboard and add rigidity to the topcase. Sixty-two heatstakes clamp the keyboard between the topcase and the chassis. The large number of heatstakes provides an even preload, which guarantees a consistent key feel.

The chassis also furnishes the negative battery contact. Incorporating the negative battery contact as an integral part of the chassis eliminated the need for a separate contact and the operations to attach it and its wire. The chassis serves as the connection between the overlay and the ESD shield located in the bottom case. Redundant cantilever contacts are employed in both cases to provide the lowest-impedance contact under all conditions. Seven snaps around the perimeter of the chassis maintain a constant preload between the two case halves. This ensures a good cosmetic fit along the 0.040-inch-wide seam. It also resists shear, greatly enhancing the torsional rigidity of the product. A closed-cell urethane foam pressure pad provides a constant force to maintain the connection between the key lines and the printed circuit board. The chassis provides the topcase with two snap details centered on the key line connections. These prevent the topcase from creeping over time under the constant force of the pressure pad in this area. A special detail is designed to stiffen the chassis around the liquid crystal display. Basically, the chassis forms a frame around the glass display to protect it from impact and bending that occur as a result of the product's being dropped.

Two narrow strips of double-sided adhesive tape are used to secure the display in the chassis. The 202 0.013-inch-wide LCD contact pads must be positioned within ±0.003 inch to make proper connection to the printed circuit board. Two zebra connectors are used to make connection between the LCD and the printed circuit board. The zebra connectors consist of two strips of silicon rubber supporting a thin row of alternating conductive (carbon loaded silicon) and insulating materials. The conductors are on a 0.004-inch pitch so that each display line connection is made with a minimum of two conductors. Two precision punched holes, which are optically registered to the printed circuit board traces, align the chassis/LCD assembly. Tabs on the chassis are inserted into the zero-clearance printed circuit board holes, permanently alligning the printed circuit board and LCD. Six twist tabs secure the assembly, providing a constant preload for the zebra connectors.

The eight-line, twenty-two character graphics display is one of the HP 48SX's most valued features. Attempting to prevent display breakage when the product was drop tested from up to two meters was one of the more interesting challenges for the designers.

The glass from which liquid crystal displays are manufactured is fragile. Glass failures are always in tension. The glass has a theoretical tensile strength of 100,000 psi. However, flaws within the glass lower its design limit to 10,000 psi. Edge defects, a result of scribing and breaking the glass to size, cause stress risers which further reduce its usable strength to only 1,000 psi. Once the design of the display mounting had been optimized, designers turned to reducing the variability in the strength of the display itself. Improving the surface finish at the scribed edge proved to be the most attractive solution. The display in the HP 48SX has a special polished finish on the glass edge where the tensile stress is highest during a front drop. This results in measurably better and more consistent drop test performance.

Printed Circuit Assembly

The HP 48SX printed circuit assembly is a collection of proven technology and innovation. To be built on the existing surface mount printed circuit assembly line, both of the new HP 48SX connectors had to be designed as robot-loadable surface mount devices.

Dominating the printed circuit assembly is the large 80-pin plug-in card connector. This custom connector accepts two cards in a staggered formation so that the label on each card can be seen. The card connector is molded with 40% glass filled PPS to survive the 225°C (437°F) infrared soldering process. Heatstakes are used to secure the card connec-

HP 48SX Custom Integrated Circuit

The HP 1LT8 IC is the single custom chip in the HP 48SX calculator. The 1LT8 IC is divided into the following functional areas:

- A 4-bit CPU with an 8-MHz clock. The 1LT8 CPU is identical to the CPU used in the HP 28S, which is a leveraged redesign of the 1LK7 CPU. The 1LT8 CPU provides faster instruction execution times but still maintains full compatibility with the 1LF2/1LK7 and the HP 71B bus architecture. The CPU internal and external data paths are 4 bits wide. Memory is accessed in 4-bit quantities (referred to as nibbles) using 20-bit addresses, yielding a physical address space of 512K bytes. The CPU internal word size is 64 bits. Operations are performed on data strings up to 16 nibbles in length.
- A memory controller capable of interfacing to five commercial byte-wide RAMs, ROMs, or plug-in ports. The purpose of the memory interface is to allow the 1LT8 chip to drive commercial RAM and ROM ICs. Since commercial memory parts are byte-wide, this requires some careful interfacing to the 4-bit world of the CPU. The same lines that go to the memory address are also used to scan the keyboard. The keyboard is connected through series resistors to the I/O lines while the memory is connected directly. This allows commercial memory ICs to be connected to the 1LT8 chip with a minimum of added pads. Each memory device can be configured by software to the required size and placement in the address space.
- A liquid crystal display (LCD) controller capable of driving a 64-way multiplexed display. This controller halts the CPU to access data in main RAM and then formats it for the LCD. It is capable of handling the softkeys in a separate memory area and scrolling the main display.
- A collection of memory mapped control registers including a 32-bit quartz-crystal-controlled timer, a 1200-to-9600-baud full-duplex UART capable of driving RS-232 or infrared-level signals, and a cyclic redundancy check (CRC) generator.
- A collection of analog circuitry including a dual power supply (4.3 volts for the system and 8.5 volts for the display), a low-battery indicator, a power-on/reset circuit, a crystal oscillator, a frequency multiplier (which generates the 8-MHz CPU clock from the 32-kHz crystal), and a display voltage generator.

The 1LT8 IC is manufactured at the Northwest IC Division of Hewlett-Packard.

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tor to the printed circuit board and to take the preload exerted by the 80 cantilevered contacts. The contacts consist of two rows of cantilevered phosphor bronze beams which are angled into the solder paste to form a butt joint. A butt joint is used because it wicks the solder up high into a fillet, preventing solder bridging between adjacent leads and allowing easier inspection. The nominal preload between the leads and the plane of the printed circuit board allows for some nonplanarity in the leads, ensuring that each lead penetrates the 0.004-inch-thick solder paste and yields a well-wetted solder joint.

The four-pin serial connector uses a similar butt type solder joint design. Like the card connector, it is a custom design using heatstakes to fixture the part during infrared soldering and to prevent the solder joints from being overstressed during use. Cantilevered arms are formed with the body of the connector to provide a slight snap upon insertion of the plug and a retention force to resist removal.

The most intensively engineered component on the printed circuit board is the 170-pin TAB-package IC. The capabilities of the IC itself are very impressive, but equally impressive is the way in which the IC is connected. Gold bumps are deposited on the IC at each contact pad. A circuit consisting of 0.003-inch-thick polyimide film with 0.003-inch-wide traces is positioned on top of the IC. The layout of the circuit is such that the traces at the inner portion of the tape actually cantilever off the polyimide substrate. These tin-plated copper beams are then aligned with the IC and simultaneously bonded. 170 inner lead bonds with a 0.005-inch pitch are made in one operation. The advantages of TAB are that its pin count is high, that it can be gang bonded, and that the polyimide substrate is punched with holes for 35-mm sprockets just like 35-mm move film (see Fig. 3 on page 42). The last feature is used to place hundreds of parts with no human intervention. The reels of burned-in and tested TAB packages are loaded onto an HP-developed TAB dispensing tool. This tool trims and forms the outer leads and presents the excised parts to a robot for placement on the printed circuit board.

The pitch of the outer leads is 0.020 inch, so accurate positioning of the TAB package on the printed circuit board is important. The position of the printed circuit board traces is determined by reading a target on the board with an optical sensor mounted on the robot. The TAB package is positioned by an annular ring of copper trace which overhangs a hole in the polyimide. The hole is exposed and etched at the same time as the 170 leads that are being positioned. This allows very accurate positioning of the leads using a simple mechanical detail. The leads are formed so they are preloaded into the solder paste. They have some compliance but the force they exert requires a TAB clamp to maintain the leads in intimate contact with the paste during the reflow operation. The steep angle at which the leads enter the paste is designed to hold the solder up high into a fillet, easing inspection and preventing solder bridging between pads.

Much design and testing went into the development of the TAB process. The results from a technical point of view far exceed all expectations.

Bottom Case Assembly

Most of the details unique to the HP 48SX are contained within the bottom case, making it possible for future products to use the HP 48SX topcase assembly.

The HP 48SX's plug-in cards are guided into the card connector through the rear of the bottom case. A box is created within the bottom case to guide the cards and prevent damage to internal components. An infrared-transmissive polycarbonate card door covers this box, keeping the cards from dislodging during a drop and forming a window over the LED and phototransistor used for infrared I/O.

Critical to a CMOS product is maintaining power to avoid losing memory. Particular attention was paid to designing the battery compartment so power could not be interrupted. The battery compartment holds three AAA batteries. The compartment is designed so that if battery leakage occurs from the vents at the negative terminals, no openings allow it into the circuit board. The battery contacts are designed to prevent fretting corrosion, a type of corrosion caused by micromotions at the contact point, which results in oxide buildup and eventual loss of contact. Extensive testing was undertaken at the very start of the project to characterize this phenomenon. Custom electrical measurement tools were employed that could detect the very onset of fretting corrosion. Batteries from U.S., European, and Japanese suppliers were exhaustively tested for compatibility with the contacts. Even the battery door was designed to prevent loss of power. The door employs a multistage snap, which prevents the batteries from becoming dislodged in drops up to two meters. The result is a design that ensures extremely reliable power even under the most extreme conditions.

A 0.006-inch-thick 3003 H18 aluminum ESD shield lines the inside of the bottom case. The shield contacts the chassis with a large-area contact. This forms a two-dimensional Faraday cage, protecting the circuitry from exposure to electric fields. The HP 48SX is designed to withstand repeated discharges with potentials up to 25 thousand volts while running without hard failures, and 15 thousand volts without any disruption of its operation. The ESD shield also provides the ground connection for the piezoelectric beeper. A single spring makes the positive connection and provides the force for the ground connection to the ESD shield. Heatstakes keep the beeper and ESD shield in place. The conical beeper spring is designed with three closed coils at the top and bottom. These coils are wider than the pitch between the open coils, preventing the springs from tangling so they can be barrel plated and vibratory-bowl-fed to a robot for totally automated placement directly on the printed circuit board.

Completing the HP 48SX package are four molded feet, which are sculptured to conform to the bottom case radius. The feet are press fit into the bottom case while it is still warm at the molding machine. A small bump on each foot provides compliance so that the HP 48SX will resist rocking even if the surface is slightly uneven.

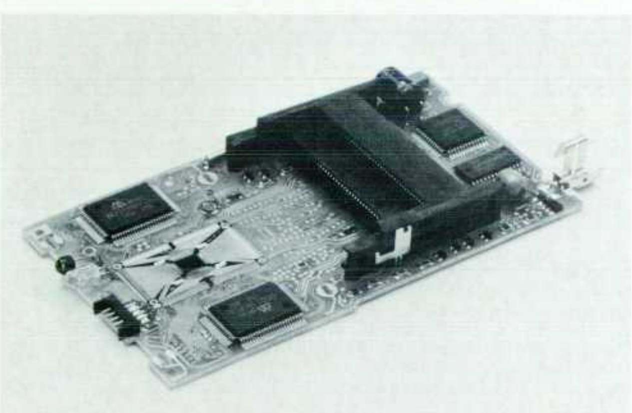


Fig. 4. *HP 48SX logic printed circuit assembly.*

Electrical System

The HP 48SX electrical system is considerably more powerful and more complex than those of previous HP handheld calculators. With its infrared and RS-232 I/O and plug-in ports, it is also more versatile. The heart of the electrical system is the 1LT8 chip, a 170-pin HP-developed IC (see box, page 30).

The HP 48SX contains two printed circuit boards. The main logic board is sandwiched between the topcase assembly and the bottom case. The Mylar domed keyboard with carbon graphite traces is housed in the topcase assembly.

The 49-key keyboard is scanned by the 1LT8 chip via multiplexed RAM and ROM address lines. Address lines A9 to A17 scan the keyboard while A0 to A5 are inputs to the 1LT8. The keyboard is read asynchronously every millisecond when the CPU drives its output register lines, A9 to A17, all high and reads its input register lines, A0 to A5. When a key is pressed, contact is made between an input register line and an output register line, putting a high level on the input register line. This high level generates an interrupt, causing software to scan the keyboard to determine which key is pressed. The **ON** key is not scanned but is wired to V_{DD}. This allows the system to be turned on while in deep sleep. The **ON** key is the only key capable of generating an interrupt and waking the system up. All key lines are isolated from the main system address lines by built-in 4-kΩ carbon graphite resistors.

The logic board contains five ICs: a 256K-byte ROM, a 32K-byte RAM, two column drivers and the 1LT8, which contains the CPU, an LCD driver controller, a memory controller, and a UART for RS-232 and IR I/O control. Also on the logic board are 36 discrete components, two 40-pin card connectors (for plug-in cards), one four-pin RS-232 connector, 202 pads for connection to the display, and 17 pads for keyboard contact. All of this is on a printed circuit board that measures 5.1 inches by 2.75 inches (see Fig. 4).

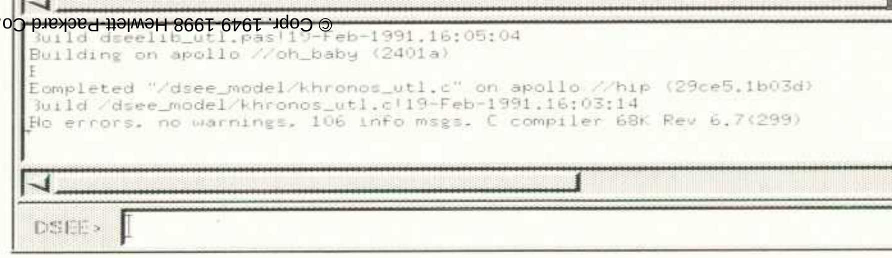
During product development, three logic boards were designed: the 256K ROM version that was released to production, a 32K OTP* EPROM version that contained self-test code used for initial shakedown and environmental testing, and a 256K EPROM version that was used for software development, debugging, and quality assurance.

For production testing, 77 logic board traces have dual test points. These test points are probed by a special test block that is connected to an HP 3065 test system. The HP 3065 tests all discrete components and ICs before the unit goes to final assembly.

The system is powered by three AAA batteries and has three power supplies, which are controlled by the 1LT8 chip. The V_H (8.1 to 8.9V) supply is used for the LCD display and RS-232 voltage swings. V_{DD} (4.1 to 4.5V) is the main logic supply. The V_{CO} (4.1 to 4.5V) supply is derived from the V_{DD} supply and is used to power the ROM and plug-in cards.

The power supply requires only two discrete diodes, an inductor, an n-channel power MOSFET, and three filter

*OTP: One-time programmable.



ical. If a critical dependency changes, DSEE will rebuild the module. If a noncritical dependency changes, DSEE will record what compiler option or source version was used, but it will not rebuild the module. There are also override mechanisms through which the user can force DSEE to rebuild even though the bound configuration thread doesn't call for a build, or not to build when DSEE thinks it has to.

Before DSEE starts building it sequences the required builds according to their interdependencies. As the user's translation script executes, it reads the desired version of each DSEE element directly out of its library. After the program is built and debugged, the user can make a release, or permanent snapshot of the bound configuration threads, binaries, sources, tools, and system model that make up the program. With this feature, when customers report a bug two years later, the engineer repairing the code can rebuild the same bits, plus the fix.

Version 3 of DSEE added support for parallel building on more than one Apollo computer at the same time. DSEE tracks the CPU utilization of candidate build computers, and starts builds on the most lightly loaded machines. Fig. 6 shows parallel builds running on several machines. The performance improvement provided by parallel building can be substantial. For example, the time to run the Ada validation test suite drops from 80 hours to 17 hours when it is built in parallel.

If an executable is compiled with an arbitrary collection of stdio.hs, it might take weeks to track down a problem caused by inconsistency in the include file. DSEE ensures that all builds use the same set of tools and system include files by building relative to a reference directory.

Heterogeneous Configuration Management

Many users want to use DSEE to develop software for non-Apollo platfor
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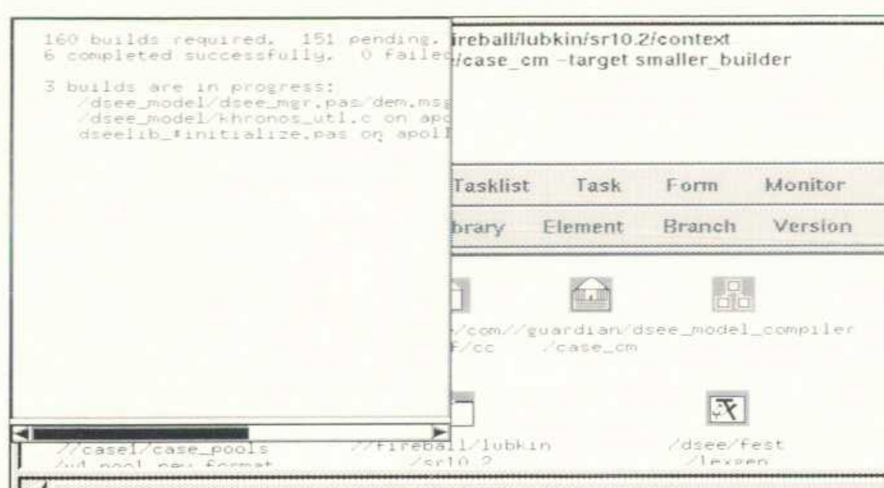

0.050-inch pitch. Towards the memory card, the pins are gold-plated and cantilevered to provide a contact force of 30 grams to 70 grams each. Towards the HP 48SX printed circuit board, the contacts are solder-plated and terminate in either a vertical or 35°-off-vertical surface mount butt joint. Since the two memory cards can share all but five pins, 35 pairs of pins are soldered to one printed circuit board pad each. The two copper ground pins, which are press fit into the body, push open the memory card shutter and provide a path for ESD from the card panels directly to the printed circuit board ground plane. The 40% glass PPS alignment comb is press fit onto the body after all 80 pins are inserted and formed, providing alignment of the pin tips onto the printed circuit board pads.

Overall, the connector measures 2.378 inches wide by 1.555 inches long and stands 0.556 inch off the printed circuit board. Although two cards are held stacked, the custom connector is less than 1.5 times the thickness of the manufacturer's original single-card connector.

While design details pertaining to body strength, pin geometry, and pin plating were adapted from the original connector, the heatstaking process to which the HP 48SX memory card connector had to conform was a challenge. Basically, after insertion through the printed circuit board, the heatstake pins are flattened using temperature and pressure, thus preventing removal. The flattened portion, called the heatstake "head", consists of very rigid and brittle glass fibers in a matrix of remelted PPS. The head must not deform under the force of the 80 preloaded contact pins during reflow soldering, or solder defects will result from lifted pin tips. In addition, the head must be tough enough to endure repeated shear stress during card insertion testing and repeated tensile stress during drop testing. To complicate matters further, the heater block on the printed circuit board assembly line needed to heatstake the memory card connector, serial connector, and TAB clamp simultaneously to minimize cycle time. To establish optimum heatstake head geometry, heater block pressure, heater temperature, and melt time, repeated staking and subsequent drop testing were conducted. Initially, ten stakes of 0.062-inch diameter were used but proved to be brittle in drop testing. Next, the stake diameter was increased to 0.118 inch but the resulting force imbalance on the heater block caused the serial connector heads to be loose. After much trial and error, the combination of four 0.118-inch-diameter heatstakes, a 0.147-inch head diameter, a 440°F heater temperature, and a 13-second melt time produced the toughest heatstake heads.

The memory card connector thus implemented combines the benefit of the manufacturer's proven design with custom details incorporated to produce the highest-performance part using predetermined assembly processes.

Performance

Tests proved the memory card and connector for the HP 48SX tested be a reliable combination. No functional problems developed after 20,000 cycles of insertion/removal life testing consisting of 1000-insertion sequences alternating with 24-hour periods in a supersoak chamber. The card survived one-meter drop testing, both alone and plugged into the calculator, as did the connector. The card also experienced no mechanical damage when exposed to 25,000-volt ESD, both alone and plugged in.

Conclusion

The goals of design and manufacturing leverage were met by using an OEM memory card and incorporating off-the-shelf connector design details where applicable. Custom features were added, however, when increased reliability and manufacturability were deemed necessary. Thus the best solution for both customer and project was implemented in the HP 48SX memory card and connector.

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Mechanical Engineer
Corvallis Division

capacitors (see Fig. 5). This is a boost-switching power supply in which the 1LT8 chip controls the current in an inductor, which is connected to the batteries, via the MOSFET. When one of the supplies (V_H or V_{DD}) is low, the 1LT8 pulses the MOSFET at a 122.84-kHz rate, increasing the inductor current. The current from the inductor is then dumped through one of the diodes, charging its filter capacitor. If both supplies are low the 1LT8 switches the charge between them at a 30.72-kHz rate.

To conserve battery life, the power supplies (and the product) have three modes of operation:

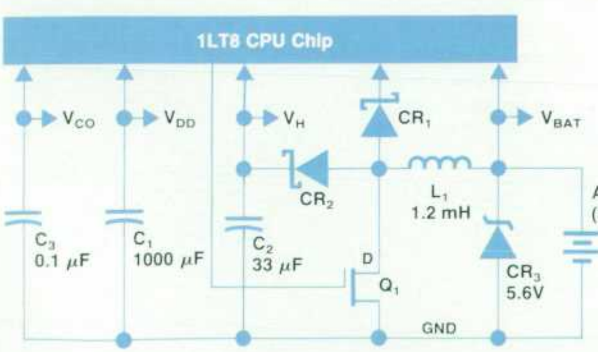

Fig. 5. *HP 48SX power supply schematic diagram.*

- Running. The 1LT8, column drivers, RAM and ROM, power supplies, and plug-in ports are all powered. Battery current is 9 mA.
- Light sleep. In this mode the 1LT8 turns off and battery current drops to 4 mA. This mode is entered whenever the CPU is inactive and a key is not being pressed. The 1LT8's display controller accesses memory every 244 μs to update the display. When the update is complete, the address lines switch and check to see if a key is pressed. Pressing any key will turn the CPU on.
- Deep sleep. All supplies are turned off and battery current drops to 12 μA. The V_{DD} supply floats to the battery voltage (V_{BAT}) which supplies power to the **ON** key, 1LT8, and RAM. This mode is entered when the CPU has been inactive for ten minutes or the unit has been turned off. To wake the system, the **ON** key must be pressed.

The 1LT8 chip also monitors the battery voltage. When the voltage falls to between 3.4 and 3.0 volts, the low-battery annunciator is turned on. If the batteries are not changed and the battery voltage falls below 1.5 volts, the system turns off. A 1000-μF capacitor maintains the V_{DD} supply for several minutes while the batteries are being changed.

The 64-row-by-131-column STN LCD is driven by two commercial column drivers, each driving 64 columns, and the 1LT8 which drives 64 rows, 3 columns, and 7 annunciator lines. The column drivers receive their data, timing and control signals, and voltage levels from the 1LT8. One of the problems with the commercial column drivers is that they require a negative voltage. To overcome this, we connect their +V line to our V_H (+8.5V) supply, their GND to V_{DD} (+4.4V) and their negative supply to GND. This requires all data and control signals received from the 1LT8 to swing from 4.4V to 8.5V. Display data is stored in system RAM, and the 1LT8 display controller interrupts the CPU for 22 to 23 μs every 244 μs to access it. As display data is received, it is serially shifted to the column drivers. When the column drivers have received 128 bits of data, they store it and output it to the display synchronously with a row driver output from the 1LT8.

For ease of expanding the HP 48SX's capabilities, dual 40-pin connectors are installed on the logic board. These connectors will accept credit-card-size plug-in RAM or ROM cards. Each connector has its own chip select line but all address and data lines are common to the internal ICs. Each connector can accept up to 128K bytes of memory.

The 1LT8 tests the connectors to determine if a card is present and if it is write protected. It does this by checking the card's write protect output. If the write protect signal is high, a card is plugged in and can be written to (RAM). If the output is low, a card is present and is write protected (RAM or ROM). If the line is floating, no card is present.

RAM cards have their own lithium keep-alive batteries. When the HP 48SX goes into deep sleep, the power supply to the cards (V_{CO} supply) is turned off. When the supply drops to between 3.9 and 3.5V, the RAM switches to its internal battery. The lithium voltage is sampled by the 1LT8, and when it drops to between 2.5 and 2.2V, a low-battery annunciator is turned on.

Acknowledgments

The design of the HP 48SX would not have been possible without the efforts of a number of people. Horst Irmscher contributed to the plastic tooling. Lonnie Byers did the printed circuit design. Pam Burkhalter and Deborah Cover were project coordinators. Recognition must also be given to the many model makers who did prototype work, Bob Livengood who gave direction and managed the early part of the project, Bonnie Miller and Donita Baron and the whole production team who helped build the prototypes, John Allen and the quality assurance team, procurement engineering, and all of the other people who contributed to the success of the Hewlett-Packard 48SX.

A project is very satisfying to the team when the objectives are met and customer response is enthusiastic. It is additionally satisfying when recognition is bestowed upon the product by related professional publications and organizations. The HP 48SX has received five awards for its innovative design including *EDN's* Innovation of the Year for computers and peripherals, and was one of ten products to receive *Electronic Products'* Product of the Year award. These honors reward the many people in HP who contributed to making the HP 48SX a successful product.