contributions of each person. Some major areas of responsibility were as follows. Gabe Eisenstein handled display and keyboard management, menus, printing, and plotting. Laurence Grodd took care of the operating system, real and complex scalar and array functions, numeric integration, and type and dispatch logic. Paul McClellan developed the solver, algebraic object parse and decompile, statistics, and unit conversions. Robert Miller worked on the programming commands, object decompile, the command catalog, low-memory handler, and binary integer operations. Charles Patton dealt with the operating system, hardware configuration, symbolic mathematics, command line parser, and program control macros. Max Jones, the author of the *Getting Started Manual* for the HP-28C, made numerous contributions to the user interface and the design of certain symbolic operations.

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Mechanical Design of the HP-18C and HP-28C Handheld Calculators

by Judith A. Layman and Mark A. Smith

THE HP-18C AND HP-28C represent a new mechanical design for HP handheld calculators. These products use a vertical clam-shell format with a simplified keyboard in a coat-pocket-size package. Using the productivity advantages provided by the use of CAD/CAM (computer-aided design and manufacturing) tools, the package was designed for manufacturability and then thoroughly tested for reliability to ensure quality performance for the customer.

Layout

The HP-18C/28C package was the first product at HP's Corvallis site to be designed principally on a CAD/CAM system. This system improved communication between design engineers and manufacturing engineering during the initial layout phase of the product. It also simplified checking tolerances and provided the expedient automatic transfer of information to the tooling shop for plastic part molds. CAD allowed easy analysis of the design such as package cross sections and the graphical simulation of case rotation (Fig. 1).

Case Design

The continual design challenge for handheld calculator products is providing more functionality in smaller packages. Many components in the HP-18C and HP-28C are integrated to provide more than one function (Fig. 2). This minimizes volume in the product and also decreases the part count for production assembly. For example, the bottom cases not only provide the cosmetic and protective shell, but also support the flexible keyboard assembly. In addition, the case half that houses the alphabetic keys is made to deflect slightly to create a latch which holds the product closed.

Heatstaking is a proven manufacturing process for providing uniform keyboard support. Using this in combination with the case assembly eliminates the need for screws. This process was easily automated because it is controllable, requires fewer parts that are easily presented to the tooling, and results in a sturdier product. The industrial design team chose to give the outside of the HP-18C and HP-28C a clean appearance by keeping the package simple and free of overlays. Because of this, reverse ejection is used to move the molding gate remnant from the cavity (outside) to the core (inside) side of the part. Contrary to convention, heatstaking is done from the top side of the keyboard. The existing keyboard overlay is used to cover the heatstake rivet heads in addition to providing the secondary function labels. The choice of polycarbonate as a case material helps ensure that the product will survive a one-meter drop on all six sides.

Dense Packaging

A hybrid printed circuit board (see article on page 25) is used because the high pin count of the two display driver ICs did not allow them to be packaged in the conventional manner for a surface-mounted device. Because of the high cost of the polyimide substrate material used for hybrid circuits, the board size was kept as small as possible. In all, five ICs, twelve discrete surface-mounted devices, and four discrete leaded devices are contained on this board. The hybrid portion on one side of the board includes two display driver chips and the CPU chip with 263 wire bonds. The chips are surrounded by a molded plastic dike and encapsulated in epoxy. On the other side of the board, all the surface-mounted devices, including two 44-pin quad packs, are loaded by robots and then vapor phase soldered. The four discrete leaded devices that cannot be vapor phase soldered have their leads preformed in a fixture and then are loaded by hand. One of these leaded devices is an infrared light-emitting diode (LED) used to transmit data to a detached optional printer via an infrared link. In addition to the components, the hybrid circuit board has contact pads for 21 key lines, a beeper, battery springs, and 178 lines to the liquid-crystal display (LCD).

LCD Interconnection

The liquid-crystal display is a four-line, 23-character dot-matrix display with seven status annunciators. The 178 pads for connecting the circuit board to the LCD have a pitch of 0.032 inch and are laid out in two rows along the edges of the hybrid circuit board. The connection between the LCD and the hybrid board uses two elastomeric (zebra) connectors. To establish and maintain proper registration between the hybrid board and the LCD pads, the position of the LCD pads is determined optically. The LCD is then secured in a stainless-steel display clip using double-sided pressure-sensitive adhesive tape. The display clip is then positioned into the hybrid board using a hole that has been precisely punched with an accuracy of ±0.002 inch relative to the display pads. This assembly is then tested and crimped.

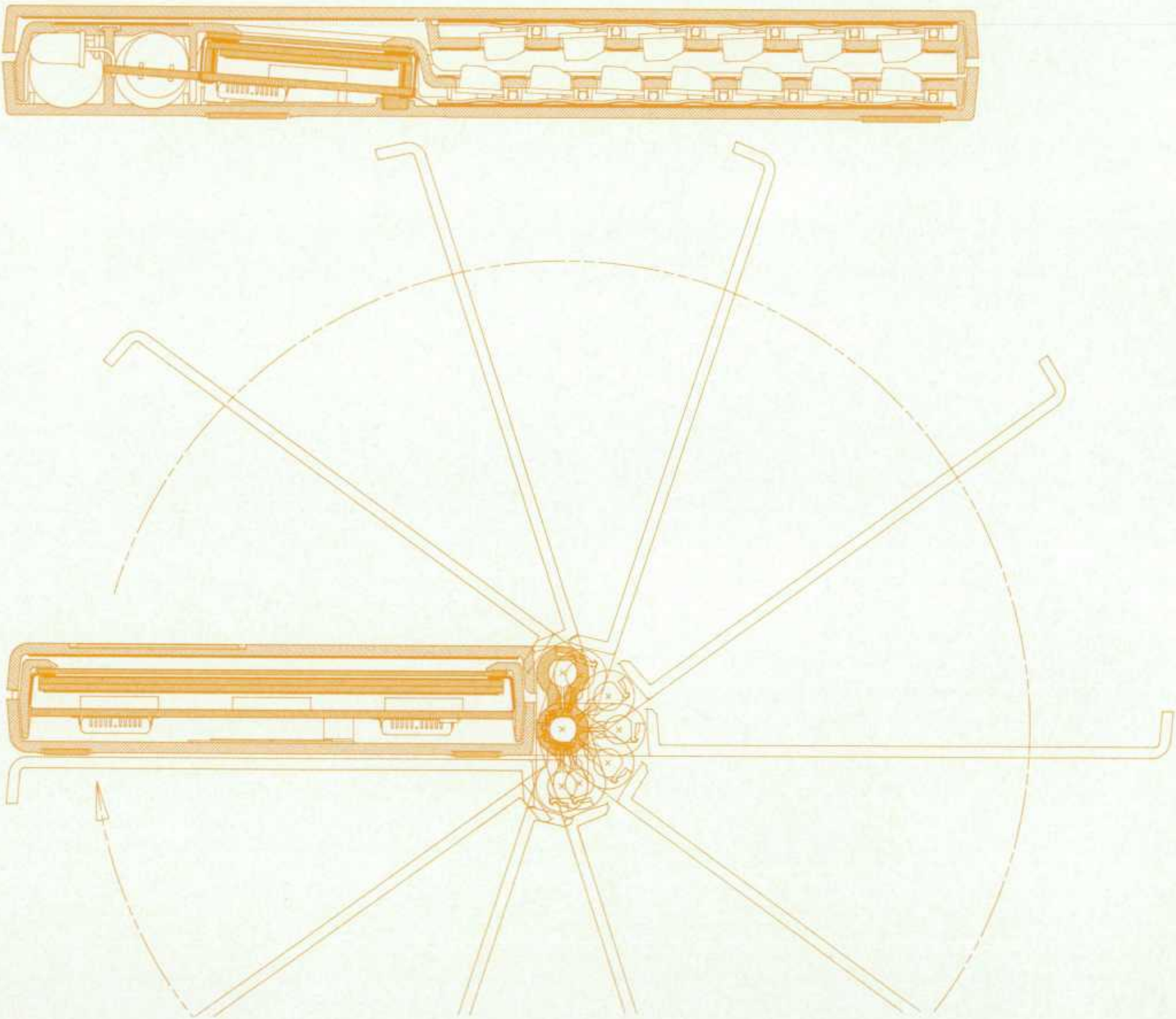

Fig. 1. *CAD drawing of a longitudinal cross section of the closed package (top) and a plot (bottom) of opened case half rotated in several positions.*

Although this basic display assembly concept has been used successfully in two earlier calculator product lines, a few improvements were made in the HP-18C Business Consultant. The first is the inclusion of a relief in the display clip along the edges of the LCD to eliminate stress concentration on the display glass. This allows the product to be dropped from a height of one meter onto all six faces with no functional damage. The second improvement is that the legs of the display clip are flared to allow a lead-in for easy assembly. The precisely punched hole not only establishes proper registration of the LCD to the hybrid board pads during assembly, but also ensures that the LCD will not shift after assembly.

Hinge Link

A compound hinge is used to connect the two halves of the HP-18C/28C case because it allows the product to be used in different positions throughout its 360 degrees of rotation (Fig. 1). By allowing full rotation, this also prevents a situation where the product might be highly stressed if dropped. Several methods of fastening the two hinge halves were investigated. These included gluing, ultrasonic welding, heatstaking, and fastening with screws. Even though it requires more complex plastic tooling, a snap-fit design is used because it offers the most repeatable, simplified process for assembly.

The hinge pins on which the link rotates perform several functions. They are conically tapered to provide axial self-centering of the hinge piece in each case half. The tip of the hinge pin is designed to preload against the inside of the hinge link. This creates frictional drag which provides a high-quality feel to the product as it is rotated. The fragile tip is supported by the main body of the hinge pin which carries any high-stress loads. The hinge pins are open on the top for inserting the interconnect portion of the keyboard into the case halves.

Keyboard and Flex Interconnect

The technology used for the integrated keyboard and flexible interconnect is conductive silver ink screened onto a polyester film substrate. This design allows a single substrate and screening to be used for both keyboards and the flexible interconnect, thus improving the reliability of the system. Twelve key lines run through the 0.140-inch inside-diameter hinge link between the two keyboard halves. Because of the trace width limitations of the screened silver ink process, a complex folded design was implemented to run four layers of the substrate through the hinge link with

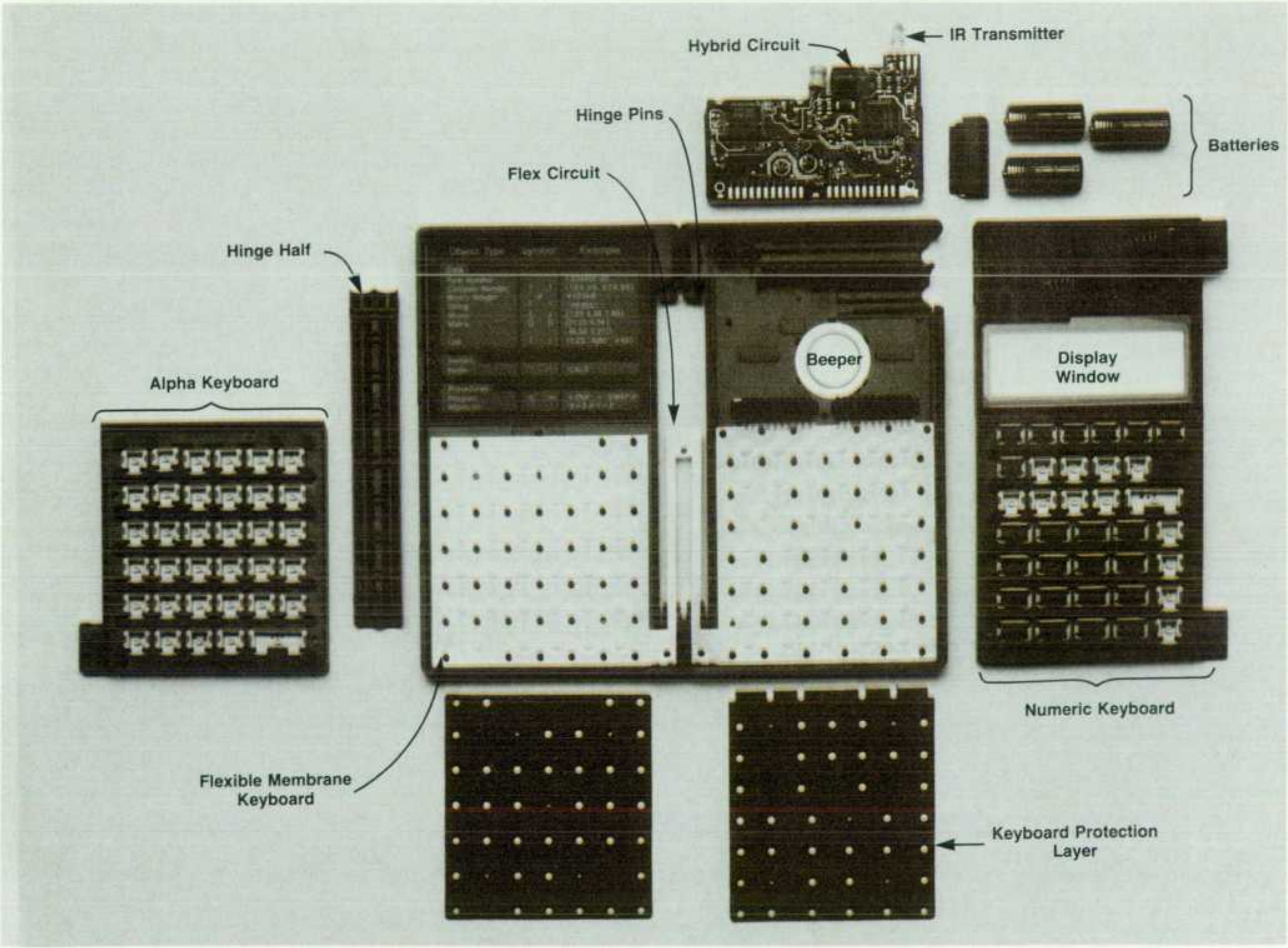

Fig. 2. *Exploded view of parts in HP-28C. The HP-18C is the same except for different key colors and labels and one less ROM on the hybrid circuit.*

each layer carrying three lines (see Fig. 3). Inside the link, the four layers run along one hinge axis, cross over to the other hinge axis, and return while being supported at both ends of each parallel segment.

The torsional stress is induced in a controlled fashion. Controlling the motion of the flexible circuit minimizes locations of stress concentration. As the product is rotated through its full range, the four flexible layers are twisted in torsion. Torsion was chosen over bending because it is less damaging to the conductive ink. The reliability of this design was verified by cycling each leg of the flex circuit through 180 degrees for two million cycles without a failure.

The two keyboards that are an integral part of this flex circuit use the same screened conductive ink for the keypads and circuit matrix. The keyboard technology is typical of that used for membrane keyboards. After the silver ink is cured, a second screening operation deposits a carbon/graphite layer over the silver ink traces. This protects the exposed key line connections to the hybrid circuit against silver migration. The carbon screening process also allowed the ready incorporation of 21 resistors for ESD (electrostatic discharge) protection. In one pass, a resistor is created in each key line by using the screened carbon to bridge a controlled gap in the silver traces. A pressure connection is made between the carbon on the key lines and the gold pads on the hybrid circuit board using two low-compression-set urethane foam pads.

Fig. 3. *Double exposure photograph showing shape of flex circuit and its location within the hinge assembly.*

Tactile feel for the 72 keys is provided by two separate dome sheets of formed polyester. A spacer layer supports the domes while also providing a vent at pressure extremes and whenever a dome is actuated. These layers are all attached to create a single part for ease of product assembly. The keyboard assembly was tested to half a million key cycles with no electrical failures and minimal degradation in tactile feel. Life testing was done at both ambient temperature and under environmental conditions of high temperature and humidity. Several iterations of key design and testing were required to achieve the life and tactile feel desired.

ESD Protection

ESD testing has consistently been a challenge in trying to release products to production on schedule. The testing typically cannot be performed until late in the project because the completed product is required. Fixes that are a result of ESD testing, therefore, do not have time to be integrated into the product properly. With this in mind, special consideration was given to ESD protection early in the design of the HP-18C and HP-28C. A prototype model was built using a similar existing chip set on a prototype hybrid circuit. Results of this testing were incorporated in the final circuit design. Additional testing revealed a localized ESD susceptibility. As a result, an aluminum shield is incorporated in the back side of the keyboard assembly. This shield provides an alternate path for electrical discharge with lower impedance and higher capacitance to ground. Hence, the HP-18C and HP-28C can survive a 25-kV discharge with no permanent damage. This is a significant achievement for a handheld portable product with no external ground.

Conclusion

The attention given to manufacturability in the initial phases of development was worth the effort. The HP-18C Business Consultant was a fast-track project requiring 18 months to develop. Even so, it made a smooth transition from the lab to production. It was up to mature volumes and yields after only four months in production.

The mechanical design of the HP-28C leveraged the work done on the HP-18C. It required only the addition of one ROM to the hybrid circuit and different overlays and key nomenclature.

Acknowledgments

The mechanical development was truly a team effort from many departments throughout the division. The lab design engineers spent long hours learning a new CAD system while designing a fast-track product. Much effort was spent to maintain reliability and manufacturability goals while on a tight schedule. Manufacturing engineering did an excellent job in designing the plastic mold and assembly tooling as well as providing early input in product design. The production team that assembled the products through the prototype builds and into production had much to do with the success of these products.