translate mode (to allow proper "untranslation"), angle mode (in case the object contains a complex number in polar form), and fraction mark (to distinguish decimal points and argument separators). The header string also allows a receiving HP 48SX to know that it should receive this object in ASCII mode. A short header is also prepended to binary objects to instruct a receiving HP 48SX to receive in binary mode. At the cost of this small amount of extra overhead, a receiving HP 48SX can correctly interpret an incoming file even if its modes are set differently than would be required for that file.

Acknowledgments

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Manufacturing the HP 48SX Calculator

Sharing manufacturing processes with earlier, simpler calculators shortened development time and improves manufacturing efficiency. The HP 48SX and the simpler calculators also share the same production line at the same time—a concept known as coproduction.

by Richard W. Riper

THE HEWLETT-PACKARD 48SX is an advanced scientific calculator that reaches new levels of capability and performance. Rather than start with a clean sheet, the design team looked to simplify HP's calculator line when developing the HP 48SX, in particular by making use of common manufacturing processes. This reduced the time to develop the calculator. Sharing common assembly techniques with other HP calculators has also led to improved production efficiency and increased flexibility.

Common Processes

When work started on the HP 48SX, design engineers were given the goal to use as many of the design concepts from a 1-and-2-line display family of calculators (HP 10, 14, 17, 20, 21, 22, 27, 32, and 42) as possible. This was done to reduce the amount of new development needed and to allow the new machine to be built on the same production line as its simpler cousins. The 1-and-2-line family set new standards in HP for calculator manufacturing efficiency and we wanted to extend this efficiency to the HP 48SX. Using proven designs shortened the typical design/build/test/redesign cycle, shortening the whole design process. It also meant that there were no new manufacturing processes to develop. This reduced the cost and delivery time for the assembly tooling. Since these tools were for familiar tasks, experience gained from the first set of tools led to better, more refined tools for the HP 48SX.

Mixed Production

The major difference between the 1-and-2-line family of calculators and the HP 48SX is in the complexity of the electronics. Most of the assembly steps needed to build the HP 48SX happen as quickly as they do for the simpler calculators. However, the HP 48SX's complexity requires inspection and test times three to four times those of the simpler machines. Since the HP 48SX is designed to be built on the same production line as the simpler models, this could have led to some major line balancing problems.

One solution to this problem would be to duplicate the inspection and test stations so that the whole line could run at the same high rate as it does for the simpler calculators. This would cost a great deal for duplicate test equipment. Also, more people would be required when building the HP 48SX, who would not be needed when the simpler product was being produced.

Another solution would be to run the whole line at a slower rate to match the longer test and inspection times. This would lead to lower efficiency, since many of the faster operations would sit idle through part of the longer cycle time.

To solve this problem, we decided to build both the HP 48SX and the simpler calculators at the same time using a process we call coproduction. One of the 1-or-2-line calculator models is built at the same time and on the same assembly line as the HP 48SX. The products are mixed

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uniformly, in the desired quantity ratio. The assembly steps shared by both machines run at the higher rate of the original 1-or-2-line assembly line. Since the test and inspection stations are peculiar to each product, the more complex HP 48SX can spend the longer time needed for testing, while several of the simpler products get tested at the same time.

The overall result is a line that builds almost as many combined units as the simpler line did by itself. It can run this mix constantly, rather than building one model of calculator for a time and then switching to the other. This eliminates large changes in the number of people required on the line and leads to better use of expensive equipment. The mix ratio is not fixed, so changes in the number of each product produced can be made to suit changes in orders.

Conveyor Production

The production of the HP 48SX is divided into two main areas: printed circuit assembly, where the circuit board is loaded, soldered, and tested, and final assembly, where the loaded circuit board is brought together with the case parts, display, and keyboard. In both areas a pallet conveyor is used to move the unit from station to station. The pallets are rectangular steel plates surrounded by plastic frames (Fig. 1). The plates have details to hold the parts in position.

The pallets ride on plastic belts, which never stop moving. At each station a stop mechanism halts the pallet while the flat belts continue to slide by underneath. At stations where accurate part location is required, the pallet is lifted off the belts and registered by the precision bushings that hold the pallet together.

Each conveyor system is made up of two sections of belt side by side. The assembly steps are done on the side nearest the operator, while the conveyor on the back side is used to move empty pallets back to the head of the line. The pallets follow this flat, rectangular loop and never need to be removed from the conveyor.

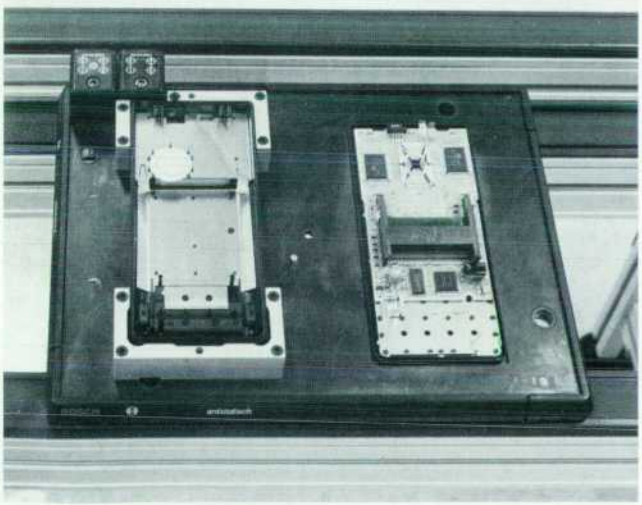

Fig. 1. *Assemblies are carried on pallets that ride on conveyor belts. The line has seven robot stations.*

Printed Circuit Assembly

Printed circuit assembly starts with an operator applying solder paste to the bare circuit board. This paste is made up of small balls of solder held in a solvent base. A printer pushes the paste out though a stencil (0.004-inch-thick brass) onto the pads for the component leads. The operator then loads the board onto an empty pallet on the conveyor (Fig. 2). All of the pallets on this conveyor are the same, and can hold the HP 48SX boards as well as those for the simpler products. The pallet then moves into the first of seven robot stations. Each station has a sensor to determine if the board on the pallet is an HP 48SX board or a board for a 1-line or 2-line calculator, so that the robot will load the correct parts.

The first robot loads the 1LT8 CPU (central processing unit) onto the HP 48SX board. Instead of using the traditional integrated circuit package consisting of a plastic body with leads, the CPU is packaged on a continuous tape (Fig. 3). This is known as TAB (tape automated bonding). Not only is this package style thinner than plastic bodies, but part handling is reduced. The ICs are simply rolled up on this reel of tape like 35-mm movie film. This tape is fed through a machine that shears the leads out from the tape and reforms the lead ends to the optimum shape for soldering. The robot first uses a reflective optical sensor in its gripper to locate the gold-plated traces and solder pads accurately on the printed circuit board. It then picks up the IC from the feeder and places it on the board, correcting its position based on the optical search.

At the second robot, connectors for the plug-in cards and input/output port are loaded. Also loaded is a TAB clamp, which will hold the leads on the TAB IC down while the solder paste is reflowed, ensuring a high-quality solder joint. After this robot the board moves into a heated press that forms rivet-type heads on plastic bosses, which will hold the connectors and the TAB clamp tightly to the board. At the third robot, the random-access memory (RAM) is loaded, along with a small coil spring that will make contact with a piezoelectric beeper. This spring eliminates the need for hand-soldered wires to the beeper. The fourth robot doesn't load any parts on the HP 48SX board, but is used on some of the simpler products.

At this point the simpler boards are completely loaded. The pallets carrying these boards are moved to the back belt, where they travel up to the second robot's area. There the second robot takes the board off the pallet and places it on a simple flat belt conveyor to move it to the solder reflow machine.

The pallets holding boards for the HP 48SX continue down to robots 5, 6, and 7, where the rest of the components are loaded. Since only a fraction of the total pallets continue on, the cycle time at these last three robots can be longer. This is a good example of where the coproduction scheme pays off. These robots can load many more parts than if they were limited to the shorter cycle time of the first four robots. After the final robot, the pallets move to the back belt, where they travel up to the second robot. As in the simpler product, the HP 48SX boards are off-loaded to solder reflow. The empty pallets continue to the head of the conveyor line, ready to repeat the process.

After loading, the boards pass down a conveyor belt to

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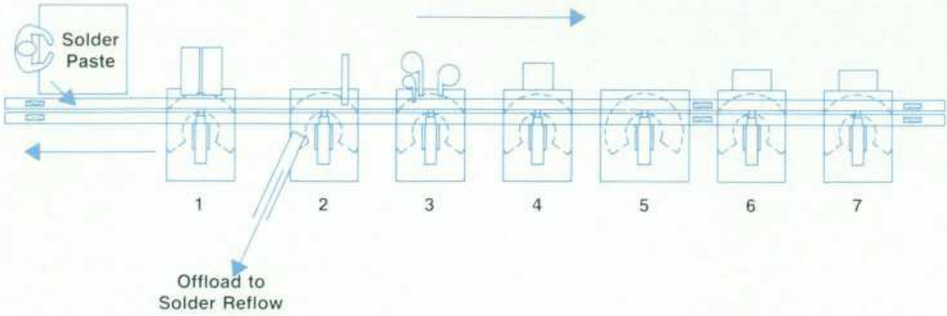

Fig. 2. *HP 48SX printed circuit assembly production line layout.*

an infrared reflow machine. The boards are then inspected under a microscope for solder joint quality and component alignment. Next the TAB clamps are removed, because there isn't room for them in the final product. A few components that are not surface mounted are added to the board by hand, and then the boards are washed to remove solder flux and other contaminants. The boards are next tested on an HP 3065 board test system, then passed on to final assembly.

Final Assembly

The final assembly line is similar to the conveyor used for printed circuit assembly, but the pallets are larger. Also, different pallets are needed for the HP 48SX and the simpler 1-and-2-line products. Sensors at each station read the pallet type and act accordingly. Instead of being totally automated, the final assembly line is a mix of manual stations with robots and other automated stations (Fig. 4).

The first station is a robot that loads plastic top and bottom cases into the pallet for the simpler calculators. This station is not used for the HP 48SX because the case parts are larger and could not be fed to the robot in the same way. At the next two stations, operators place case parts for the HP 48SX into the pallet and load keyboard parts for both products.

The next station is a pair of robots that work together to align and load the liquid crystal display (LCD) into the metal chassis and then load the chassis into the topcase, which is waiting on the pallet. One robot picks the LCD up from its shipping tray and places thin strips of double-stick tape along both long edges. It then passes the LCD off to the other robot. This second robot locates the LCD's contact pads under a reflective sensor and uses this search information to place the LCD accurately into the metal chassis. Locating details on the chassis accurately carry this alignment to the pads on the circuit board.

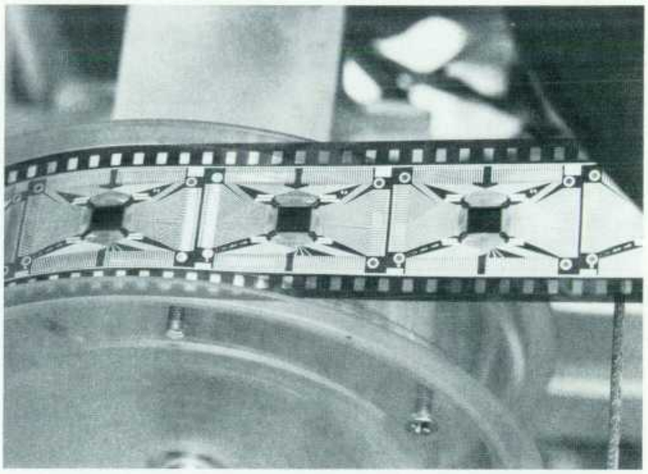

Fig. 3. *1LT8 ICs are packaged for tape automated bonding (TAB) and can be handled like movie film.*

The pallet then travels into the first of four heated presses used to hold the calculator together; no screws are used. Three of these four heatstakers work on both product types, so the product type is sensed and the top portion of the tool automatically shifts the correct heater block into place. The fourth heatstaker is only used on the 1-and-2-line products, so the HP 48SX pallets simply pass through. The first heatstaker forms rivet-style heads on bosses in the topcase,

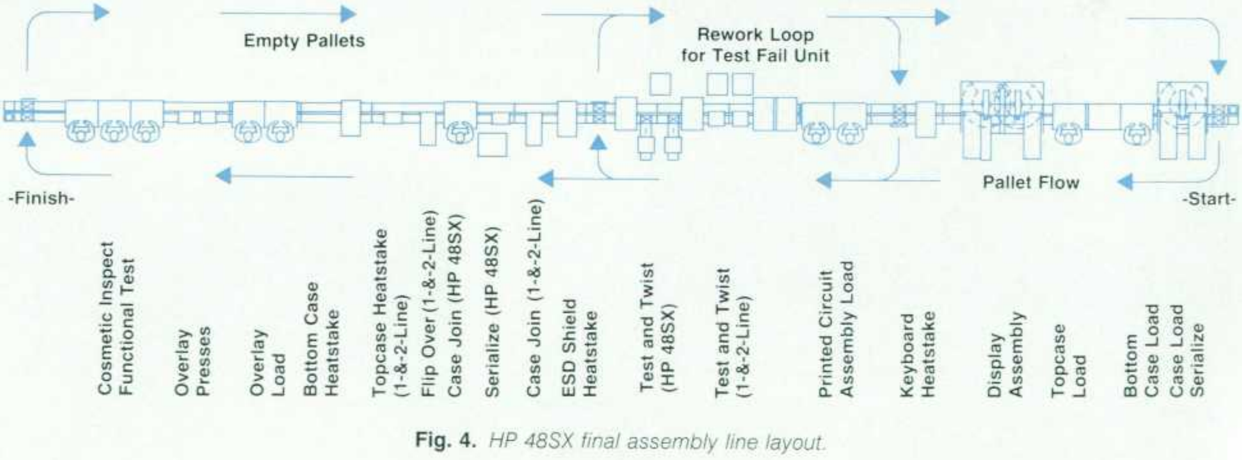

Fig. 4. *HP 48SX final assembly line layout.*

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holding the chassis and keyboard parts tightly together.

The pallet now moves into a set of manual stations where the printed circuit assemblies are added. Elastomeric connectors known as zebra strips (for the alternating black carbon conductor bars), which make the electrical connection between the LCD and the printed circuit assembly, are loaded onto the LCD, and then the printed circuit assembly is added.

Automated Vision and Functional Tests

The pallet then moves to a series of testers. The testers for the 1-and-2-line family are located on the conveyor, and the HP 48SX pallets pass through these without stopping. The testers for the HP 48SX are located to the side of the main conveyor line just past the simpler testers. The HP 48SX pallets are automatically moved off the main line into the testers. This allows them to take longer to test without holding up movement of the simpler products, which test much more quickly. After testing, the HP 48SX pallets are moved back onto the main line to continue to the next station.

In each tester, the pallet is raised up against a test block (Fig. 5). This block contains spring-loaded probes which make electrical contact to test pads on the circuit board. Small air-powered cylinders can press on each key on the keyboard of the upside-down calculator, both to test the keyboard and to start a number of self-tests that are built into each calculator. Cameras mounted at the bottom of the tester look up at the display and an automated vision system checks to ensure that the whole display "lights up" as the calculator runs through its self tests. HP instruments check current levels and measure the operating frequency.

Once the calculator passes these tests, metal tabs formed as part of the chassis are automatically twisted to hold the printed circuit assembly, zebra strips, and LCD together. If the unit fails the test, a mechanical test failed code is set on a code block mounted on the pallet. Following the test stations is a mechanism to move failed pallets to the back belt, where they will loop back to the stations where the printed circuit assembly was loaded for evaluation. To aid rework, an error reporting system using an HP Vectra personal computer lets the operator at that station know which test the unit failed.

The pallets then pass through a heatstaker to stake in an aluminum electrostatic discharge shield and the piezoelectric beeper. At the next manual station, additional shielding parts are added by an operator and the cases on the HP 48SX are joined together. The cases are joined on the simpler products automatically. The calculators then pass through a pair of heatstakers to join the cases together permanently. Again, no screws are used.

Next, an operator places a printed overlay over the keyboard, which is pressed on at the next station. At the last set of stations, operators load the batteries and doors, and perform cosmetic and functional tests. The calculators are now ready to be packaged with the instruction manual in the box for shipment to the dealer.

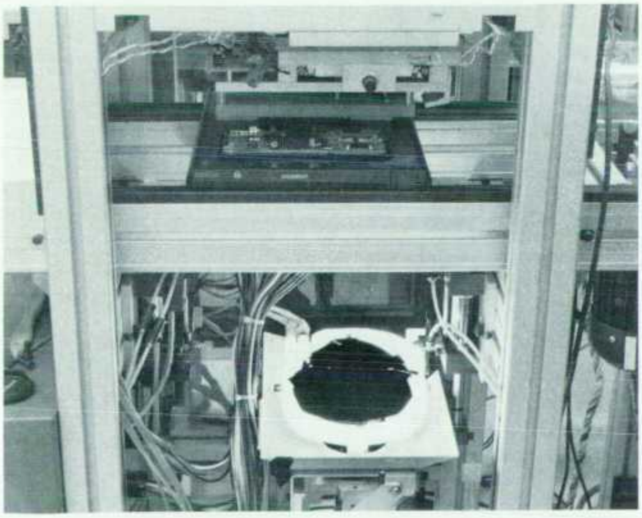

Fig. 5. *This tester uses two cameras and an automated vision system to inspect the calculator's display.*

Conclusion

As described above, many of the assembly steps for the HP 48SX are shared with similar steps for the simpler 1-and-2-line series of calculators. By basing the design of the HP 48SX on this earlier product line, the same production line can be used to build both type of products. By using the coproduction techniques described above, both products can be built at the same time, leading to better production efficiency and people balancing.

Acknowledgments

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