A Miniature Surface Mount Reflective Optical Shaft Encoder

The HEDR-8000 Series encoders provide two-channel medium-resolution encoding performance in a very small SO-8 plastic package. Their small size, reflective operation, and low cost enable customers to design them into applications that were impossible for earlier encoders, such as feedback sensing for the miniature motors used in copiers, cameras, vending machines, and card readers.

by Ram S. Krishnan, Thomas J. Lugaresi, and Richard Ruh

Imagine a position servo sensor so small that it can fit almost anywhere. Put it in a surface mount package and give it a price comparable to slot encoders that have much lower resolution. Such a sensor became reality with the introduction of the HP HEDR-8000 Series reflective optical surface mount encoders (Fig. 1).

The HEDR-8000 Series encoders deliver HP reflective optical encoder technology in a surface mount package. They provide two-channel medium-resolution (75 and 150 lines per inch) encoding performance in a very small SO-8 (small outline 8-pin) clear plastic package. The reflective technology of the HEDR-8000 Series encoders is inherently different from other HP encoder modules, which use transmissive technology with light passing through a codewheel or codestrip. In the HEDR-8000 Series encoders, light reflects off the codewheel or codestrip.

HP’s shaft encoders (sensors that measure the position of a rotating motor shaft) have always been based on optoelectronics, thus providing noncontact measurement and far greater reliability than contact potentiometers. The first HP encoders were the HEDS-5000/6000 complete encoder packages, introduced in 1979. In 1987 HP introduced the low-cost HEDS-9100 encoder module, a small optoelectronic package that must be combined with a coded wheel or strip to function as a position sensor. A powerful feature of this encoder was that it could be assembled with a codewheel without the need for “phasing,” or adjusting the position of the encoder to bring the output signals within the desired specification. The HEDS-9100 family quickly became the position sensors of choice in the computer peripherals market. But by 1989, low-cost inkjet printers were introduced and needed a smaller, lower-cost solution. This led to the introduction of the HEDS-9700 family of encoders, which were smaller, less expensive, and ultrareliable, supported high-volume assembly, and offered excellent performance.

The HEDR-8000 Series encoders were developed because new low-end printers required a smaller, less expensive encoder. Customers were redefining high-volume assembly capability to include surface mountability and infrared reflow oven
solderability. The design objectives for the HEDR-8000 Series encoder project were low cost, surface mount capability, and medium resolution.

The design was influenced by a new product introduced for front-panel applications, the HP HRPG family, which proved that reflective sensors were not only feasible and inexpensive, but had the added advantage of stackability, that is, the codewheel or codestrip could be mounted on top of the encoder module and not “through” it, as required by the previous transmissive models. This not only enhances the high-volume assemblability, but also allows the encoder to be placed in space-limited applications.

The small size, reflective operation, and low cost of the HEDR-8000 Series encoders enable customers to design them into applications that were difficult for earlier encoders. One such application is feedback sensing for the miniature motors used in copiers, cameras, vending machines, and card-readers.

Fig. 2 shows the evolution of HP optical encoders in cost and size.

![Fig. 2. Reduction in size and cost of HP encoders.](image)

**Basic Operating Principles**

The HEDR-8000 Series encoders combines an emitter and a detector in a single surface mount SO-8 package. As shown in the block diagram, Fig. 3, the HEDR-8000 Series encoders have three key parts: a single LED light source, a photodetector IC, and a pair of lenses molded into the package. The lens over the LED focuses light onto the codewheel, and the image of the codewheel is reflected back through the lens to the photodetector IC.

![Fig. 3. HEDR-8000 Series encoder block diagram.](image)

As the codewheel rotates, an alternating pattern of light and dark corresponding to the pattern on the codewheel falls on the photodiodes. This light pattern is used to produce internal signals \( A \) and \( B \) and their complements \( \overline{A} \) and \( \overline{B} \). These signals are fed through comparators to produce the final digital outputs for Channels A and B.

The HEDR-8000 Series encoders' performance is characterized by the quality and consistency of the two encoding signals, Channel A and Channel B. These signals have a quadrature relationship so that, as the codewheel passes in one direction, Channel A leads Channel B, and as the codewheel passes in the other direction, Channel B leads Channel A. Fig. 4 shows the output waveforms. Although the HEDR-8000 Series encoders match HEDS-9700 resolution, they have generally lower performance than their transmissive predecessors, in part because of smaller size and lower cost.

**Encoder Design**

The first steps in the design determined the lens sizes required to gather sufficient light, the minimum detector IC size needed, and the minimum number of pins needed. A requirement was to use a standard surface mount package to allow
customers to use standard assembly equipment such as pick-and-place machines. These requirements were traded off with the customers’ need for a small, fit-anywhere size to arrive at the SO-8 package. However, the height was increased beyond the standard to allow for the proper optical focal length of the lenses, after it was determined that this did not interfere with the operation of standard assembly equipment. The low-cost objectives are achieved by using a transfer molding process to form the package and lenses all at the same time. The plastic used to encapsulate the parts needed to be optically clear and transfer moldable. Not many such materials exist, but a moldable material was found that transmits about 90% of the light at the LED’s wavelength of 700 nanometers. A book mold was built to mold prototype parts.

Existing ICs were used in early prototypes, and codewheels were made by photocopying a jail-bar pattern onto a reflective mylar sheet and cutting out the disks. Amazingly, they worked!

In its final configuration, an HEDR-8000 Series encoder consists of a clear plastic SO-8 package with two lenses located on the top of the package. A slit-shaped light-emitting diode (LED) that emits red light at 700 nanometers is under one lens and a silicon bipolar detector IC is under the other lens.

**Optical Design**

The reflectivity of the codewheel surface is an important factor affecting the performance of the HEDR-8000 Series encoders. The ideal codewheel reflective surface is a mirror that reflects almost all the light incident on it. The mirror-like property is specified by a measure called specular reflectance. Specular reflectance (or specularity) is the percentage of the incident light that is reflected back at an angle equal to the angle of incidence. This is the property of a surface not to scatter light. For example, a shiny surface with a rough finish will reflect most of the light incident upon it, but will also scatter the light, and therefore will have a low specular reflectance. The specular reflectance can be measured with a device called a scatterometer. For proper operation, a minimum of 60% specular reflectance is required in the reflective portions of the codewheel and a maximum of 10% specular reflectance is required in the nonreflective portions. For example, metalized mylar codewheels having 85% specularity and nickel-plated stainless-steel codewheels with typically 65% specularity both perform well with the HEDR-8000 Series encoders.

The HEDR-8000 Series encoder lenses are spherical and have a radius of curvature of about 0.7 mm. Different lens options such as aspherical lenses, cylindrical lenses, no lenses, and others were tried by simulation. Spherical lenses were chosen for their ease and low cost of manufacturing and verification (no null correctors required), as well as their performance (significantly better than no lenses or cylindrical lenses).

The performance of the part was simulated using ASAP, a ray-trace program, with manufacturing tolerances included. The results indicated that the HEDR-8000 Series encoders would work robustly over the normal manufacturing tolerances, but the encoding performance would vary because of these tolerances.

ASAP was used to vary manufacturing tolerances such as die attach locations and lens dimensional variations. Customer assembly tolerances such as codewheel gap were also simulated. These studies were used to determine the optimal lens radius and height.

A critical design parameter is the included angle, defined as the angle subtended by the radii of the lenses. If the lenses were complete hemispheres, the included angle would be 180 degrees. Once again, optical simulations were used to determine the optimum included angle.

**Detector IC**

The starting point for the the HEDR-8000 Series encoder integrated circuit was the existing two-channel integrated circuit used in HP’s high-performance encoders. The challenge was to take this basic design and reduce it in size to meet the low-cost objectives of the HEDR-8000 Series encoders without sacrificing performance.

The encoder circuit contains the following functions:

- Detection, implemented by photodiodes
- Amplification of photocurrents
- Production of stable bias currents
- Current-to-digital-output-voltage conversion with hysteresis
- Provision for testability.

The photodiode area was shrunk by a factor of 10 relative to the existing detector IC and the loss of signal was made up by increasing the lens magnification and the amplifier gain.

The amplifier was reduced to one third of its original number of devices by trading off sensitivity to transistor gain changes resulting from IC process variations. The HEDR-8000 Series encoder amplifier has a very large dynamic range and can work with a wide range of photocurrents. Common-mode rejection is provided by using a differential input configuration.

For the HEDR-8000 Series encoders, a new hysteresis circuit was designed using a geometric offset in the emitter instead of using a resistor as in the previous circuits. This allowed the removal of two large resistors while maintaining the function of the circuit. The hysteresis was found to perform better than the original circuit over temperature and $V_{cc}$ variations, but is more sensitive to variations in the IC fabrication process.

No changes were made to the other functions.

The detector IC is a 5V bipolar device. Fig. 5 shows a partial layout and Fig. 6 shows the equivalent schematic circuit.

![Fig. 5. Partial layout of the detector IC.](image)

![Fig. 6. Block diagram of the detector IC.](image)

The circuit uses one or more sets of two photodiodes for each channel. The number of sets depends on the resolution of the particular model. For example, the 75-line-per-inch version has one set (a total of four photodiodes) and the 150-line-per-inch version has two sets (a total of eight photodiodes). The photodiodes in each set are laid out next to each other and labeled A, B, A', and B', in that order. If there is more than one set, the pattern repeats. The photodiodes are placed so that the image of
each set spans the pitch of the codewheel, that is, the width of each photodiode is a quarter of the codewheel pitch. The width of the photodiode at the detector IC is reduced by the magnification factor of the lens, which is 4/3. Thus, for the 150-line-per-inch version, the photodiode width is 0.0013 inch. This reduced photodiode size allows a reduction in the size and therefore the cost of the detector IC.

The $A$ and $\overline{A}$ photodiodes together produce the $A$ channel output and the $B$ and $\overline{B}$ photodiodes together produce the $B$ channel output, 90 electrical degrees apart from $A$. The layout of the photodiodes is such that the $A$ and $B$ photocurrents are 90 electrical degrees apart in phase, the $A$ and $\overline{A}$ photocurrents are 180 electrical degrees apart in phase, and the $B$ and $\overline{B}$ photocurrents are 180 electrical degrees apart in phase. The $A$ and $\overline{A}$ photocurrents are amplified and fed into a comparator. The comparator’s output, which mirrors the encoder’s output, switches high when the $A$ photocurrent is greater than the $\overline{A}$ photocurrent, and switches low when the $A$ photocurrent is less than the $\overline{A}$ photocurrent. This push-pull operation allows consistent performance despite changing LED performance (which happens over time and varying temperature conditions).

If there is more than one set of photodiodes, the photocurrents from all of the $A$ photodiodes are averaged, and similarly for $\overline{A}$, $B$, and $\overline{B}$, thus minimizing the effect of codewheel irregularity.

Crosstalk between the two output channels is minimized by using an internal capacitor to slow the output transistor fall time to about 100 ns and by separation and shielding of sensitive signals.

The circuit is designed so that one of the photocurrents must be greater than the other by 10% to cause a change of output state. This hysteresis effect is important in preventing oscillations for the case when currents from $A$ and $\overline{A}$ are exactly equal and spurious noise can cause a change in the output state.

The detector IC design is flexible enough to allow resolutions of 68 lines per inch to 200 lines per inch, with a change in the photodiode pitch.

**Performance**

The HEDR-8000 Series encoders are very tolerant to radial misalignment, tangential misalignment, axial play of the shaft on which the codewheel is mounted, LED current, and codewheel/codestrip gap. Fig. 7 shows typical performance for the 75-line-per-inch version.
Manufacturing
The HEDR-8000 Series encoders required completely new processes for manufacturing. It was decided at the outset that key processes such as transfer molding of the package would be developed in San Jose, California and then installed in Singapore after the bugs were worked out. However, an important distinction from previous encoder lines was that the entire manufacturing line would be set up in Singapore from the beginning. The line was set up to produce small volumes so that customers could begin to design the HEDR-8000 Series encoders into their applications. The theory was that by the time customers were ready to buy the encoders in volume, a high-capacity line would be in place.

Project Management Issues
Many HEDR-8000 Series encoder customers are in Japan, the manufacturing line is in Singapore, and most of the development staff is in San Jose. Such projects are complicated by their logistics, not to mention the different cultures and time zones. A good many trips were made to Japan and Singapore, and these went a long way to improve personal relationships among team members and move the project along in its difficult times.

The project also experimented with two new concepts. One, called iterative product development, involved building prototypes and presenting them to key customers for evaluation. A firm product definition was avoided until the prototypes got to a stage where the customers were clearly delighted with the concept. At this point, the product specification was finalized and the development began in earnest.

The second experiment involved producing parts on temporary or low-capacity tooling. The intent was to speed up market entry and subsequently develop a high-volume line while the customers evaluated the product in their applications.

Acknowledgments
Bob Steward and Bill Beecher originally identified the market trend that defined the HEDR-8000 Series encoders. For this and for their unwavering support through the many organizational debates, the authors are grateful. John Uebbing co-conceived the optics in the HEDR-8000 and was always a willing sounding board for ideas. Many thanks are due team members from other functions, including Marilyn Wong, Chris Yien, and George Willis, and team members from Singapore, including Richard Gan, Soon Hing Chan, and Wai Kuin Kwok. Many others also helped in support functions and are too numerous to acknowledge individually. Thanks are also due Victor Loewen, Dave Pitou, and Chris Togami for creating the original concepts and the ensuing excitement in the product.

Bibliography