Linear and Rotary Encoders are Evolving to Meet Demands

Application Bulletin 206

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Introduction
Linear and rotary encoders have come in a wide variety of design styles over the years, the most common being rotary switches, potentiometers, capacitive, magnetic, and optical types. The optical encoder has become the most popular of these encoding methods due to its long life, simplicity of construction, versatility, high accuracy and high resolution. This application bulletin will briefly define an optical encoder, and bring the designer up to date on encoder terminology, design techniques and limitations. Refer to Application Bulletins 201 and 203 for additional information.

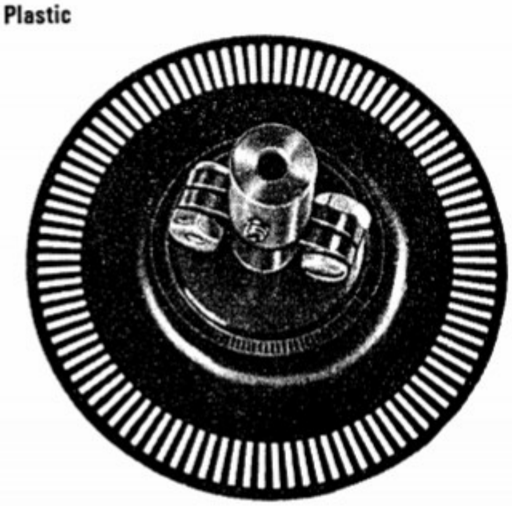
General Discussion
An encoder is an electromechanical device used to monitor the motion or position of an operating mechanism, and the translate that information into a useful output. We define an optical encoder as an optoelectronic device which translates rotational or linear movement into some usable electronic waveform. Encoders generally consist of two parts; a "moving unit" which is attached to and moves with the device being monitored. The moving unit contains information to be sensed by the "stationary unit." The stationary unit consists of an LED and a photosensor (or a combination of LEDs and photosensors) mounted on opposite sides of a slot through which the moving unit passes, thereby modulating the light path (s).

The types of output information available are speed, velocity (speed with direction) and relative or absolute positioning. The output can be either analog or digital depending on the type of photosensor used. For a more thorough description of encoding techniques, refer to Optek Bulletin 201.

Encoder Components
A. <u>The Moving Unit</u>
The modulation of the light path(s) in the optical encoder is accomplished by the moving unit which is a "scale" (linear encoder) or a "disc" (rotational encoder). The scale or disc is attached to the operating mechanism and contains alternating areas of transparency and opacity to the light path. The size, shape, and frequency of these areas is the basis of the output information supplied by the encoder.

A number of materials are currently being used in the fabrication of scale and disc components. A few examples are given below and on page 2 with the advantages and disadvantages of each.

Molded Plastic



Advantages	Disadvantages
Low cost	Resolution of < 50 lines per inch
Durable	Relative mechanical and thermal instability

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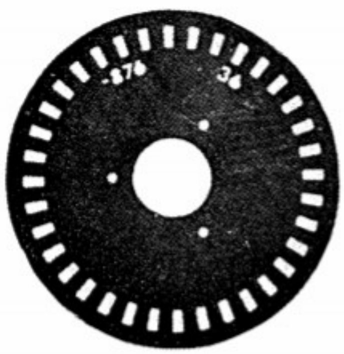
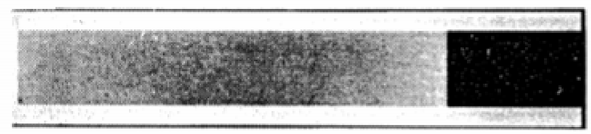
Etched Metal



Advantages	Disadvantages
Reasonable cost	Resolution of < 150 lines per inch
Resistant to shock and vibration	
Good thermal stability	

Mylar Film



Advantages	Disadvantages
Reasonable cost	Mechanical, thermal, and humidity instability
Resolution of < 1000 lines per inch	Can be damaged in handling

Chrome on Glass

Advantages	Disadvantages
Resolution of > 2500 lines per inch	High cost
Excellent optical quality	Can be damaged in handling
Excellent mechanical, thermal and humidity stability	

B. The Stationary Unit

The stationary unit contains all the components necessary to generate the light source and sense its intensity as it is being modulated by the scale or disc. It sometimes contains the signal conditioning electronics required to amplify and/or digitize the output of the encoder. The light source consists of one or more incandescent lamps or light emitting diodes and may include lensing to improve the collimation of the light source. Most recent optical encoders use LEDs because of their lower cost, longer life, better shock resistance, and lower power consumption.

(1) Sensing Elements

Solar cells, photodiodes, phototransistors, and photosensitive integrated circuits are all used in optical encoders. The Optek Photologic series of photosensors was developed to enable the stationary unit to provide a digital output which can be directly interfaced with TTl, LSTTL, CMOS, and other standard logic families.

(2) Apertures and Reticles

One method of improving encoder resolution is the “sizing down” of the photosensitive area. This is done by placing a reticle with

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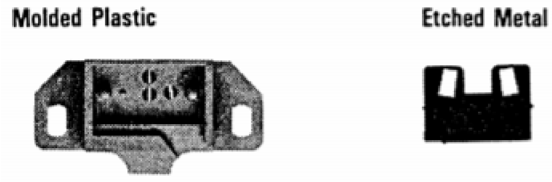
a certain aperture size in front of the photosensor. The reticle contains a pattern of transparent and opaque areas which are optically mated to the scale or disc being "read." The transparent areas are referred to as apertures, and one or more apertures may be placed in the reticle over the photosensor in high resolution.

Figure 1 – Examples of Reticles



(3) Signal Conditioning Electronics
Resistors, capacitors, integrated circuits, input/output connectors, and additional components are often contained on a printed circuit board in the stationary unit. These components are used to amplify the photosensor output and interface the encoder to the system in which it is used.

(4) Housing
The components used in the construction of the stationary unit are usually held in position by mounting them into a metal or plastic housing. The housing is then mounted to the operating mechanism (motor, etc.) to optimize the interface between the moving and stationary units. In some cases, the moving and stationary units are packaged together and external linkages are provided for coupling the packaged encoder to the operating mechanism.

Operating Principles

A. Modulating the Light Source

The movement of the scale or disc in the light path is the source of modulation of the light in an optical encoder. A simple example of modulation would be the interruption of the light beam in a burglar alarm. The momentary interruption or reduction of light is easily detected. As resolution requirements increase, apertures become smaller and detection becomes more difficult. An improvement over standard aperturing is the light shutter.

B. The Light Shutter

The reticles used in optical encoders may contain 20 or more alternating transparent/opaque areas in front of each sensor. If the moving unit and the reticle have identically matched patterns of 50% duty cycle (transparent and opaque areas are the same width) then the emitted light received by the sensor will be at a maximum when all the transparent areas of the reticle are exactly superimposed designs. Some examples of reticles made of the same materials, and intended to be used with the scale and disc samples discussed earlier, are shown in figure 1. The same advantages and disadvantages apply. In the case of molded plastic, apertures are molded right into the housing.

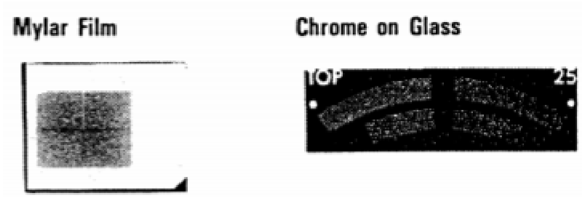
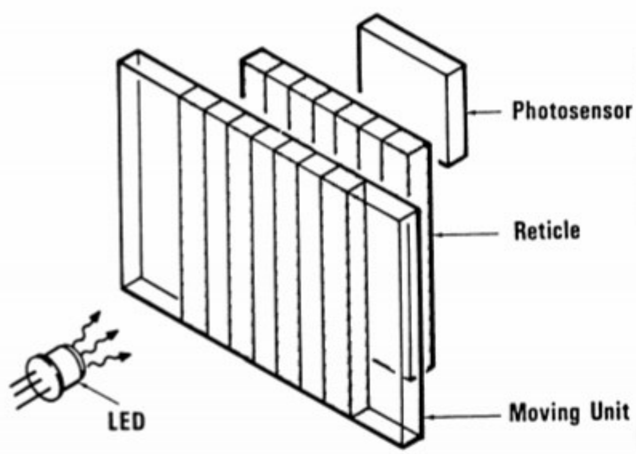


Figure 2 – Light Shutter

When the moving unit moves one area width, the emitted light received by the sensor will be at a minimum, but not zero since in this type of light modulation there is some slight light leakage around the opaque areas in the moving unit. This sequence repeats for each cycle of movement, and is referred to as the "light shutter" because of the similarity of operation to a camera shutter.



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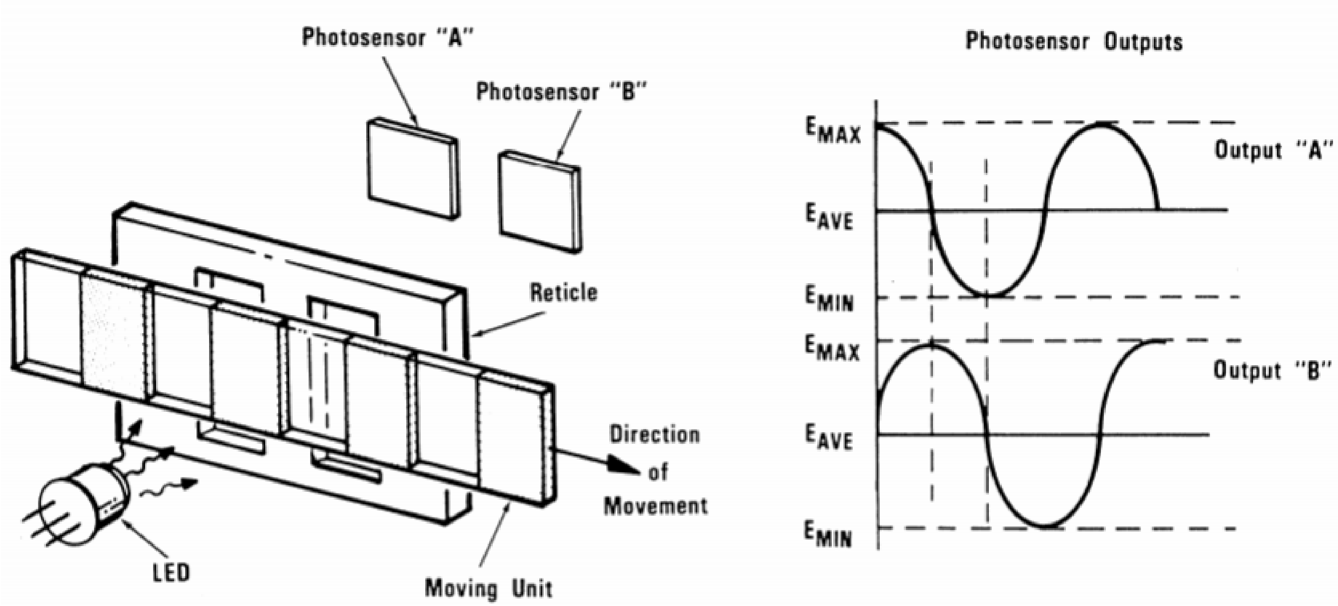
C. Quadrature
Determination of direction of movement of the moving unit is also possible by locating two photosensors in the encoder and mechanically shifting the aperture pattern in the reticle over one photosensor, 1/4 cycle from the aperture pattern in the reticle over the other photosensor as shown. This causes a “phase shift” in the output of one photosenor relative to the other and indicates direction of motion. This phase relationship is called “Quadrature,” and is illustrated in figure 3.

Figure 3 – Quadrature



The output from photosensor “A” rises 90° ahead of the output from photosensor “B” indicating that the moving unit is moving to the right. If the moving unit were moving to the left, the output from “B” would be 90° ahead of “A”. For more information on dual channel encoding refer to Application Bulletin 203.

Sensing Circuit Techniques
The use of the light shutter permits the design of an optical encoder capable of very high resolution. However, electrical and mechanical errors must be considered and compensated for in the design to allow full use of this capability.

A. Single-Ended Encoders
The use of a single photosensor to generate each output in an optical encoder is inherently limited. LEDs will degrade with time and temperature resulting in changes in the output signal shape and level. However, if performance requirements are not severe, the single ended approach offers the simplest design approach and lower cost.

B. Convoluted Duty Cycle Encoders
The use of 50% duty cycle components in a single-ended encoder does not necessarily guarantee the optimum in performance. A reduction in the duty cycle of the reticle (making the opaque area wider than the transparent area) and an increase in LED drive current will improve the output performance of an encoder that is being digitized by a comparator. Operating a phototransistor at very high light conditions will tend to reduce its frequency response. The use of convoluted duty cycle usually requires the use of a photodiode type of photosensor. Optek’s Photologic series of photosensors are ideally suited for the type of application.

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C. Automatic Gain Control
An unmodulated photosensor channel can be incorporated exclusively to monitor the intensity of the emitted light from the LED. Feedback is then provided to a drive circuit powering the LED. This compensates for degradation from all causes and will enhance the long term performance of the encoder. The trade-off is in increased cost and circuit complexity.

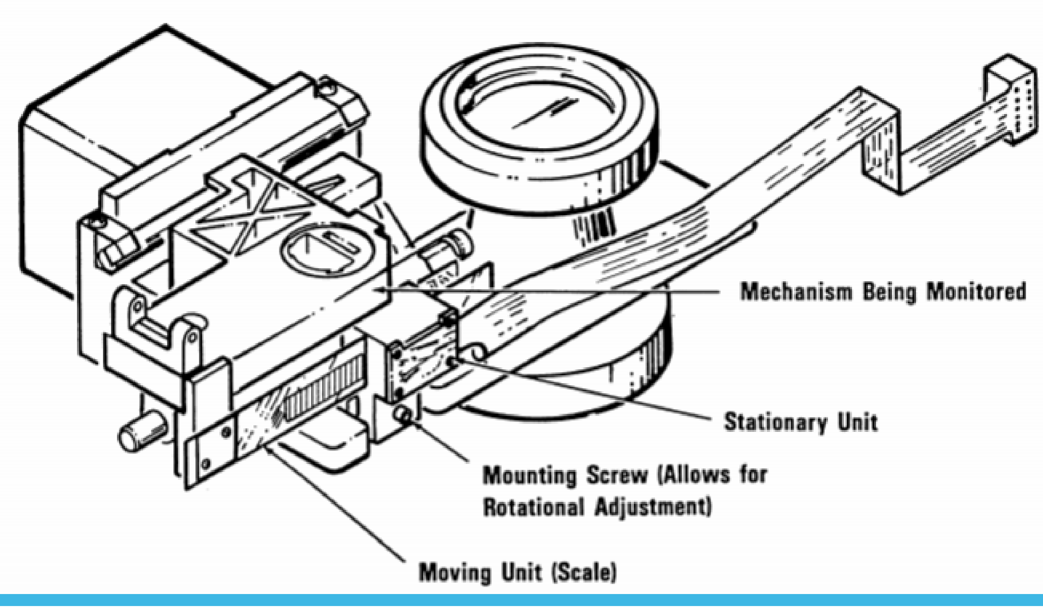
D. Differential Circuitry
By generating quadrature in "complementary format" (i.e. 0°, 180°, 90°, 270°), the complementary phases may be differentially amplified or compared to generate the required quadrature output (generally 0° and 90°). This approach allows noise reduction and drift compensation. An additional advantage is the ability to operate high gain phototransistors in the non-saturated mode, thereby improving frequency response. The negatives are increased cost and circuit complexity.

E. Zero Referencing
Many encoders provide speed, velocity, and relative position data, but a starting position must be known to derive true position. An extra photosensor is sometimes provided to look for a single point of transparency of opacity at a specific place on the scale or disc. The sensing of this point is used to zero the counting circuitry driven by the encoder during power-up, or any time an error in count is detected.

Mechanical Interfacing
The best possible performance from an optical encoder is dependent on the proper selection of materials, circuit design and the integrity with which the encoder is attached to the operating mechanism. The space between the scale or disc and the reticle must be as narrow as possible and consistently maintained throughout the travel of the moving unit. Variations will result in degraded performance.

A. Mounting the Moving Unit
A properly designed housing provides for flatness across the surface of the reticle at some absolute height from the mounting surface of the stationary unit. This allows the positioning of the moving unit to be performed as a separate operation. Disc mounting requires two steps (1) affixing the disc to a hub using adhesive and/or a clamp ring; (2) mounting the hub/disc to the device being monitored using adhesives and/or set screws located 90° apart on the hub. Linear scales are mounted to a bracket on the operating mechanism at one or both ends. The entire scale must travel evenly and precisely through both end extremes. A typical encoder mounting application is illustrated in figure 4.

Figure 4 – Encoder Mounting



B. Mounting the Stationary Unit

The stationary unit should be designed to allow rotational or displacement adjustments. These adjustments compensate for mechanical tolerances in fabrication of the stationary and moving units that could prohibit the final fine tuning needed by the light shutter.

C. Maintaining the Gap

The distance between the scale or disc, and the reticle is referred to as the "gap." In photo-emulsion type light shutter components, the emulsion sides should be facing each other and a minimum space maintained to prevent abrasive damage. If the properties of the operating mechanism and the housing are known (thermal expansion, end play, eccentricity, etc.) the moving unit can be mounted using a spacer. Then the fixed unit is simply inserted, adjusted and locked in place. Another solution is a sliding bearing inserted between the shutter components to prevent wear damage.

D. Error Related to the Gap

A gap of zero width allows for complete modulation of the emitted light shutter. Any increase in gap width will result in reduced modulation where:

$$\%\ \text{Modulation} = \frac{\text{Signal Output (ACVpp)}}{\text{Max. Achievable Undistorted Signal Output}} \times 100$$

The reduced modulation is caused by non-collimated light from the LED (i.e. leakage around the shutter components) and becomes substantial as the gap width approaches the aperture width in size.

Variations in the gap during the travel of the moving unit result in amplitude modulation. These variations affect the interface circuitry driven by the encoder during signal conditioning or digitizing and can cause clipping, positive pulse width modulation or variation in time between output pulses (in a pulse output encoder).

The quadrature relationship between the output channels will vary as the sum of the error on each individual channel.

E. Performance Limits

The optical encoder provides direction information only as long as the quadrature related signals occur in proper sequence. Any phase, duty cycle, or modulation error that interrupts or reverses this sequence defines the ultimate limit of an incremental encoder.

Conclusion

Optical sensing is currently the most versatile method of motion sensing in rotary and linear applications. LED and photosensitive integrated circuit technology, along with innovative sensing techniques are keeping pace with today's sensing requirements so that the advantages of long life, high resolution, reliable operation in harsh environments, and low cost are available in almost any motion sensing application.

J. W. Davidson, III
Lowell Johnson

TT Electronics | Optek Technology
1645 Wallace Drive, Suite 130, Carrollton, TX, USA 75006 |Ph: +1 972-323-2300
www.ttelectronics.com | sensors@ttelectronics.com