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MOTION DESIGN GUIDE

ENCODERS

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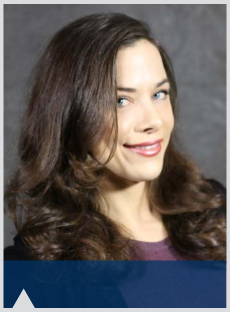
ENCODERS DESIGN GUIDE

Often found inside compact servomotors, hollow-bore encoders such as this Model 260 from Encoder Products Co. can also be applied as a retrofit feedback option for a fan-ventilated motor.

Automation of discrete motion tasks is core to modern manufacturing. Encoder technologies in these designs use optical, capacitive, inductive, or magnetic operation to track speed and position.

As we'll detail in this Design Guide, the most suitable encoder type for a given machine function depends on the required accuracy, ruggedness, and signal type — as well as cost constraints.



LISA EITEL
Engineer Editor

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INTRODUCTION TO ENCODERS

For applications with excessive dust and debris, encoders with IP50 or higher ratings are recommended. Insulation-manufacturing image courtesy Encoder Products Co. (EPC)

Shown here are views of just one of dozens of motion subsystems on a Roche cobas. This fluid-transfer head assembly includes two linear guide rails with blocks; two detachable Roche tip needles with liquid transfer sample loops; two stainless-steel trapezoidal leadscrews with Derlin anti-backlash nuts; one double-channel capacitive sensing PCB; an LTC485 RS485 interface transceiver; an isolated dc-dc converter; two coreless servomotors; and two optical quadrature encoders for closed-loop control.

Encoders are essential motion components that provide feedback on system speed and position. For their operation, they use signals based on light, magnetism, or magnetostrictive material behavior. Broadly speaking, encoders are at their core sensors — *transducers* that *transduce* or convert one form of energy (typically electromagnetic or mechanical) to another. Transducers qualify as sensors when their primary function is to detect some physical condition in space, transduce electrically or mechanically collected information about that condition into some other electrical signal, and then send that signal onward to a controller.

Feedback devices qualify as encoders if they employ a gradated or marked (coded) wheel or tape of some type. After all, the meaning of encode is to convert some message or other information into a coded format that the receiver (in automation, a controller) can understand.

Of course, there are all sorts of encoding processes related to other industries beyond ours of automation — including the encoding of data related to audio and video (in the film industry) and programming systems.

Process-automation sensor technologies generally include those to track temperature, pressure, and flow.

(continued)

INTRODUCTION TO ENCODERS

Shown here is the marked wheel of an optical encoder.

Discrete-automation sensor technologies generally include those to track torque, force and torque (F/T), vibration, acceleration, distance, object presence or proximity, and (the primary focus of this Design Guide) angle, speed, and position. All these sensor types have advanced over the last two decades … as has their programmability and connectivity to support IoT functions. After all, sensors are core to the IIoT so very reliant on data collection and systems monitoring for predictive maintenance and integration with enterprise-level operations.

No matter their format or special features, sensor and encoder measurements can be:

- Relative or incremental — expressing values that relate to a floating or arbitrary start point
- Absolute — expressing values in relation to some fixed reference.

What's more, sensor output can be analog (with an electrical signal format that's continuous and proportional to the measured condition) or digital (with an electrical signal format that changes incremental value in response to the measured condition).

Discrete-automation sensor technologies specific to motion are further classified by what exactly they track. Sensing rotary speed is usually via tachometers, sensors, or rotary encoders. Sensing linear speed is usually via rotary encoders (employing controls capable of estimating position based on motor-shaft actions) or the direct measurements of linear encoders. Sensing rotary or linear position is usually via encoders or position sensors. These devices track axes or objects in translational (linear) planes by indicating positions related to a reference … and position at any given time depends on the distance traversed by an object or axis. Also called linear displacement, this is a vector value … as it defines both a distance quantity and a direction of movement.

Bottlecap application image via Dreamstime

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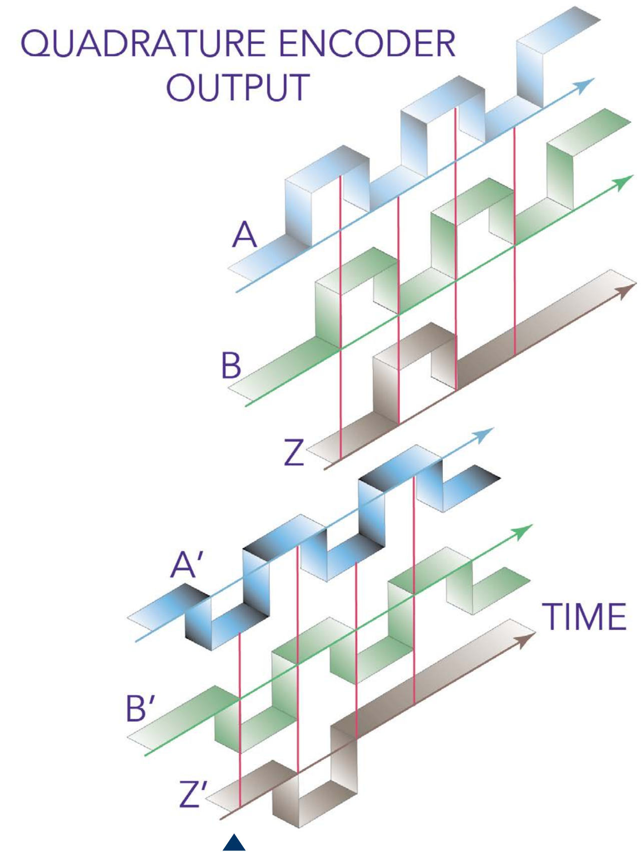
INTRODUCTION TO ENCODERS



Shown here are encoder outputs transmitted as quadrature signals.

In fact, most suppliers of linear position sensors for industrial applications also supply sensors to track angular position, acceleration, object tilt, and (relative to process control) fluid-level sensors. That's because these components leverage many of the same core technologies (based on induction, magnetism, and so on) as linear-motion sensors.

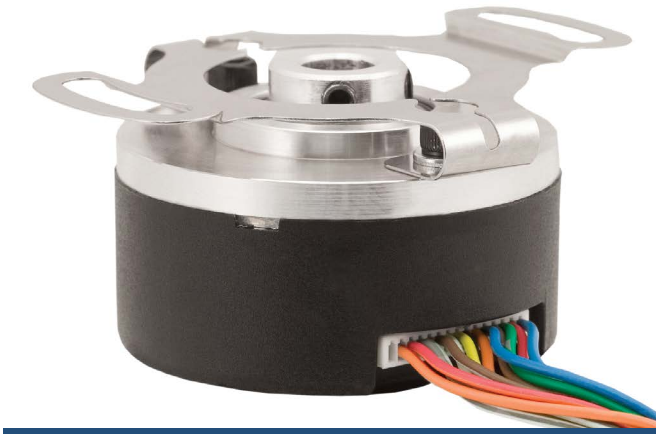
There are variations in how specific industries (such as packaging and 3D printing) use the terminology described above. Where motion system design isn't core to an industry's systems, engineers may simply consider encoders (especially incremental encoders) to be a subtype of position sensor specifically relating to motion control. That's especially true for autonomous designs also employing vehicle-position sensing based on light amplification by stimulated emission of radiation (laser) and light detection and ranging (lidar) technologies with time-of-flight, triangulation, or other forms of tracking. Elsewhere, engineers use encoders to refer to those components associated with a given motor or linear actuator in the design … and position sensors to refer to feedback components associated with functions at the furthest reaches of the design's axes.

> Linear position sensors facilitate two system capabilities — continuous position feedback as well as the ability to program machine controls to respond when the tracked axis reaches a key location.

POSITION SENSORS VERSUS ENCODERS: LINEAR VERSIONS COMPARED

Consider the specific case of linear encoders to encode position as a quadrature signal pairs — whether analog (sinewave) or digital (squarewave). Because the position-data-conversion process essentially takes place within a linear encoder's scale-reading subcomponent, it's logical that such technologies are called encoders.

In contrast, the term linear position sensor often indicates some device employing an analog or digital signal-generating assembly based on electromechanical potentiometric, electrolytic, capacitive, inductive, or magnetic operation — with the latter including various magnetoresistive, Hall effect, and magnetostrictive permutations. Where the term linear position sensor is used without any other context, it usually implies a linear variable differential transformer (LVDT) — one particularly common and useful technology. Elsewhere, the term *linear displacement transducer* (abbreviated LDT) is used. This usually refers to magnetostrictive-based linear sensors that compete with potentiometric-based sensors in the machine tool, office automation, and paper-printing industries. That said, some technical sources use LDT to also refer to linear potentiometers as well as draw-wire linear transducers containing rotary potentiometers.



The Model 15T with 15-pin-header and ribbon cable option from Encoder Products Co. is commonly used in servomotor applications with commutation feedback.

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INTRODUCTION TO ENCODERS

Design engineers should note that linear-position sensors and linear encoders always add overall linear-system cost, but it's usually a justified expenditure. For example, adding linear encoders to ballscrew-driven axes can often let design engineers specify screws of a lower accuracy class. After all, the linear encoder feedback on such an axis can help the controller compensate for any ballscrew positioning errors.

Of course, the top benefit of linear-position feedback though is how it vastly improves the quality of cutting, dispensing, and other positioning-related machine operations. For example, without linear-feedback components, many laboratory-automation installations today wouldn't be able to successfully employ the low-cost stepper-motor actuators so common to this industry. In these designs, linear-position sensors aid in precise positioning and prevent damage to the machine as well as expensive (and often irreplaceable) test samples.

TOP DEVELOPMENT IN ENCODER TECHNOLOGY = PROGRAMMABILITY

As we'll explore in this Design Guide, encoder technologies have evolved over the last several decades — prompting increased use of encoders with embedded microprocessors to:

- Run advanced signal-processing software for accurate and dynamic response
- Leverage the ruggedness of solid-state electronics for component compactness and reliability

Related: [Why do some encoders have embedded microprocessors for signal processing?]()

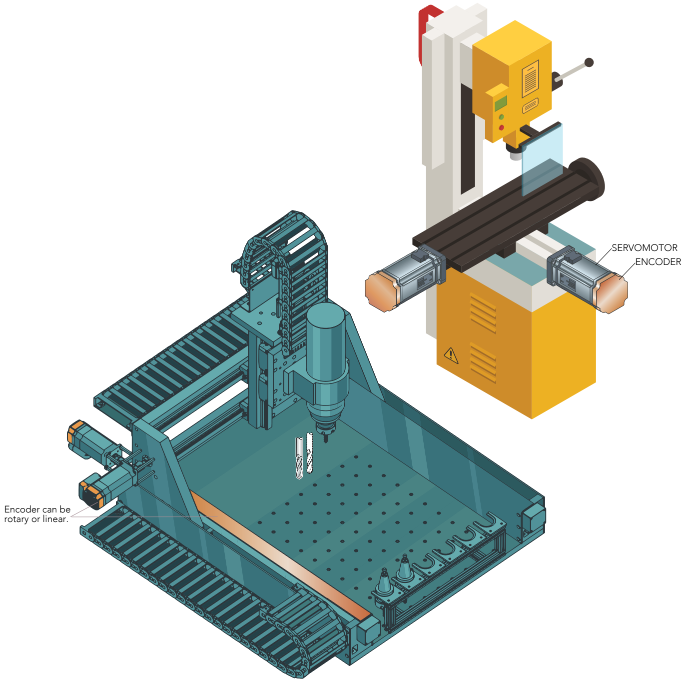
Some such programmable encoders include features for easy installation and alignment — along with wider applicability thanks to the programmability of encoder resolution (often as counts per revolution or CPR), output type, quadrature direction if applicable, and various output-waveform values. In fact, programmability can in some cases let designers configure a single encoder model to multiple machine axes — so that one encoder comes to supersede various part numbers. That in turn can trim inventory costs and downtime should one axis necessitate the replacement of its encoder.

▲

For rugged applications such as fast-revving motors, encoders such as the Model 25T are designed with cooling capabilities and come with optional corrosion-resistant components.

COMPARING INCREMENTAL AND ABSOLUTE ENCODERS — AND THEIR OUTPUT SIGNALS

Robot-guided surgery designs use zero-backlash actuators with encoder-equipped gearheads to let surgeons position various end effectors with top accuracy.



Small-part machine-tool applications (including drilling applications such as the one shown here) can be negatively affected by imperfect mechanical-drive accuracy. Here, encoders can help boost output quality by tracking axes' positions and helping controls compensate for the inaccuracies of a machine tools' own components.

Rotary encoders (whether absolute or incremental) track speed and position. But rotary incremental encoders work by generating a series of pulses during movement. The encoder disc (sporting marks or slots) attaches to a power-transmission shaft, and a stationary pickup device mounts nearby. When the shaft and disc turn, the pickup tracks the motion to output the relative position. Such encoders generally supply square-wave signals in two channels that are offset from each other by 90° — in other words, 90° out of phase. Each increment of rotation spurs an output signal.

Note that rotary incremental encoders begin counting from zero each time the encoder powers up, and electronics store the data in an external buffer or counter. This is true regardless of where the shaft is radially. So incremental encoders must always come back to a reference point … both when the machine initially starts and whenever something interrupts its power supply. Here, battery backups can help eliminate the need for re-homing after shutdowns.

Such incremental encoders are generally simpler and cheaper than absolute encoders.

Incremental encoders work by producing a specific number of equally spaced pulses per revolution (PPR) or per distance as pulses per millimeter (PPM) or pulses per inch abbreviated PPI. When one set of pulses or output channel is used, the encoder can determine position only. But most incremental encoders use quadrature output, which consists of two channels, typically called channel A and channel B that are 90° out of phase. Quadrature output allows

(continued)

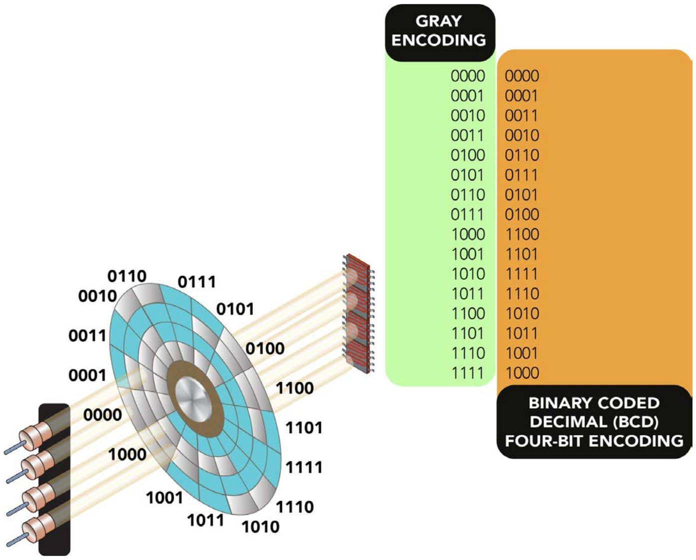
COMPARING INCREMENTAL AND ABSOLUTE ENCODERS — AND THEIR OUTPUT SIGNALS

the encoder to also sense direction, by determining which channel is leading and which is following. Some incremental encoders also produce a third channel with a single pulse, commonly referred to as channel Z or channel I. This channel serves as the index or reference position for homing.

Later in this Design Guide, we'll cover quadrature output and three types of encoding used with it — X1, X2, or X4. As we'll explore, the difference between these encoding types is simply which edges of which channel are counted during movement. That said, the influence of encoding type on encoder resolution is significant.

MORE ON ABSOLUTE ENCODER TYPES AND APPLICATIONS

Absolute encoders have an encoder disc (sporting marks or slots) on a power-transmission shaft and a stationary pickup, but the disc marks output a unique code for each shaft position. Absolute encoders are either single-turn or multiturn encoders. Single turn absolute encoders can verify position within a single turn of the encoder shaft. This makes them useful for short travel situations. In contrast, multiturn absolute encoders are better for more complex or longer positioning situations. More on multiturn encoders later in this Design Guide.



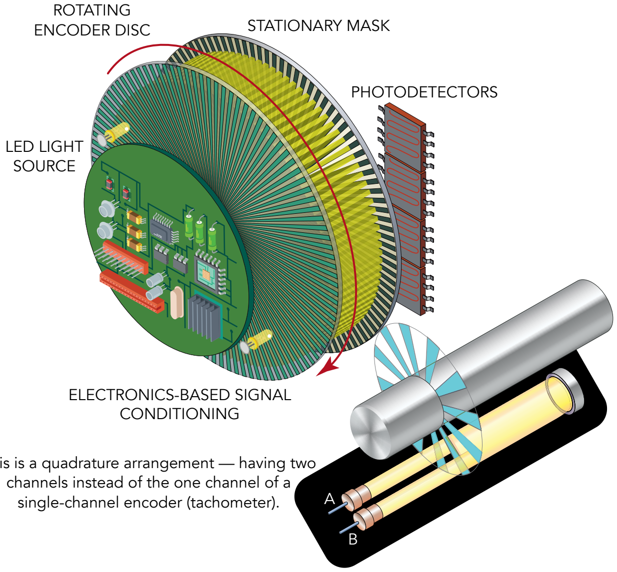
GRAY ENCODING	BINARY CODED DECIMAL (BCD) FOUR-BIT ENCODING
0000	0000
0001	0001
0010	0011
0011	0010
0100	0110
0101	0111
0110	0101
0111	0100
1000	1100
1001	1101
1010	1111
1011	1110
1100	1010
1101	1011
1110	1001
1111	1000

This is Gray-code encoding.

Engineers generally classify absolute encoders by the number of their output bits, which correlates to the number of the disc's tracks — and the maximum rotary angle the encoder registers.

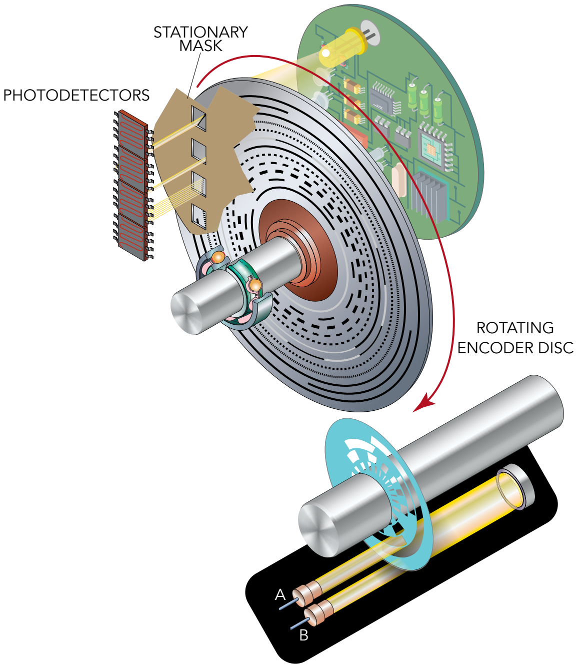
Absolute rotary encoders have the advantage of nonvolatile memory — meaning they can report position even after power fails and returns. So even if something moves the machine shaft when

INCREMENTAL ENCODER — OPTICAL EXAMPLE



This is a quadrature arrangement — having two channels instead of the one channel of a single-channel encoder (tachometer).

ABSOLUTE ENCODER — OPTICAL EXAMPLE



Absolute encoders include a sensing mode involving a disc or tape with distinctive marks capable of yielding a unique signal for each shaft or axis position. The electronics within an absolute encoder interpret detector tracking of the coded element to generate unique position information.

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COMPARING INCREMENTAL AND ABSOLUTE ENCODERS — AND THEIR OUTPUT SIGNALS

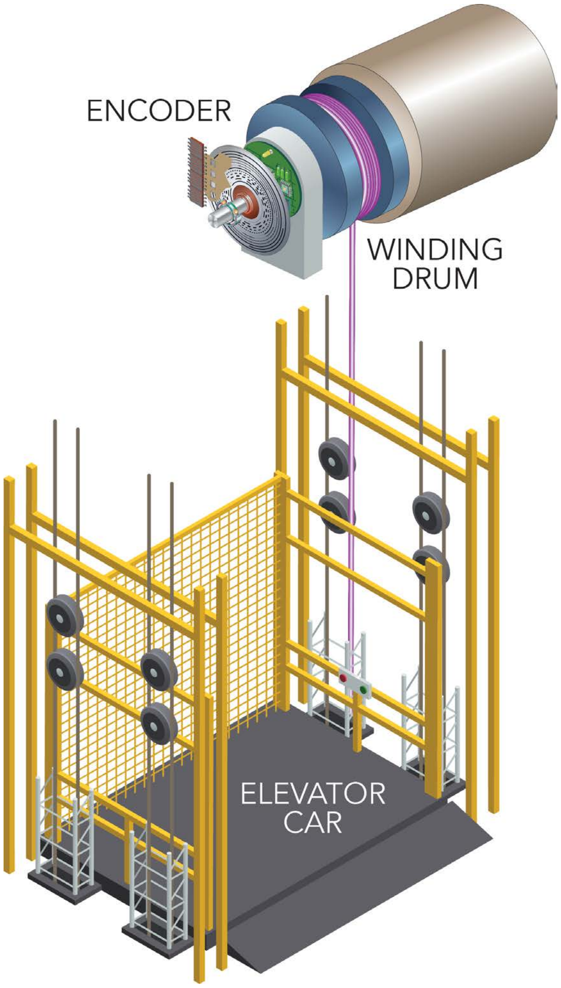
power is off, an absolute encoder keeps track of the rotary-position change when the machine powers on again. Usually, electronics store this information as binary code … ideally Gray binary code. Absolute rotary encoders can operate point-to-point as well. They are useful in situations where safety is a concern because they position whenever machines power on. Immunity to electrical noise is another benefit.

One caveat: Absolute rotary encoders are generally more expensive than incremental encoders. However, the cost of absolute encoders has steadily decreased over the last decade, and that's caused steady increase of their use.

NEXT STEPS FOR SELECTING ENCODERS FOR MOTION DESIGNS

Once the decision has been made regarding incremental or absolute feedback, the next consideration is the operation type. Optical encoders — which use a light source and a photodetector to determine position — are the gold standard for encoder technology, as their resolution is exceptional and operation well proven. Caveats are that they must be protected from dust ingress (which can degrade signal transmission) and require a precisely set gap between the sensor and the scale.

Next most common are magnetic encoders. These use a magnetic reader head and a magnetic scale to determine position. Recent decades have seen improved magnetic-encoder designs with high resolution … especially useful where an axis runs in settings with copious dirt, debris, or liquid contamination — or exposure to shock and vibration. One caveat is that magnetic encoders are sensitive to magnetic chips such as steel or iron, as the latter may interfere with the encoders' internal magnetic fields.



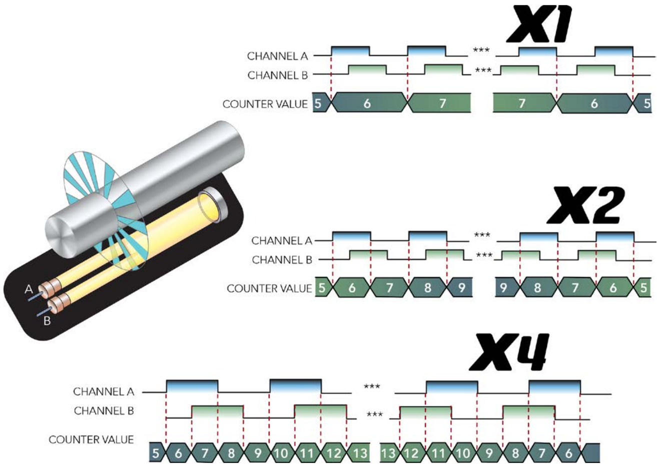
One of myriad applications for absolute encoders are on the winding drums of certain elevator types.

DEEPER DIVE ON INCREMENTAL ENCODERS

Encoder Products Co. Accu-CoderPro programmable incremental encoders include the Model 25SP and the Model 58TP. The programmable Model 25SP Accu-CoderPro encoder shown here has a servo mount.

Incremental encoders are a relatively simple and inexpensive feedback option for applications where rehoming after a power loss is not detrimental to the process. With quadrature output, incremental encoders can achieve high resolution … even at high speeds.

Earlier in this Design Guide, we covered the basics of incremental encoder construction — including kit types, modular types, and more. Now we'll review the concepts of encoding type and pulses per revolution (PPR) — and how to specify suitable types and values for a given axis.



With X1 encoding, either the rising or the falling edge of channel A is counted. Notice that when channel B is leading, the movement is considered counterclockwise or reverse … and the count is decreased. With X2 encoding both the rising and falling edges of channel A are counted. With X4 encoding, both the rising and falling edges of channels A and B are counted.

Recall that with quadrature output, three types of encoding can be used — X1, X2, or X4. The difference between these encoding types is simply which edges of which channel are counted during movement. That said, the influence of encoding type on encoder resolution is significant.

With X1 encoding, either the rising (also called leading) or the falling (also called following) edge of channel A is counted. If channel A leads channel B, the rising edge is counted, and the movement is forward, or clockwise. Conversely, if channel B leads channel A, the falling edge is counted … and the movement is backwards or counterclockwise.

When X2 encoding is used, both the rising and falling edges of channel A are counted. This doubles the number of pulses that are counted for each rotation or linear distance, which in turn doubles the encoder's resolution. X4 encoding goes one step further, to count both the rising and falling edges of both channels A and B, which quadruples the number of pulses and increases resolution fourfold as well.

For rotary encoders, position is calculated by dividing the number of edges counted by the product of the number of pulses per revolution and the encoding type described above (X1, X2, or X4) and then multiplying the result by 360 to get degrees of motion:

(continued)

DEEPER DIVE ON INCREMENTAL ENCODERS

$$\text{Degrees } (°) = \frac{\text{Edge count}}{x \cdot N} \cdot 360°$$

Where x = The type of encoding (whether X1, X2, or X4) and N = Number of pulses generated per shaft revolution. For linear encoders, position is calculated by dividing the number of edges counted by the product of the number pulses per revolution and the encoding type. This result is then multiplied by the inverse of the pulses per millimeter or per inch:

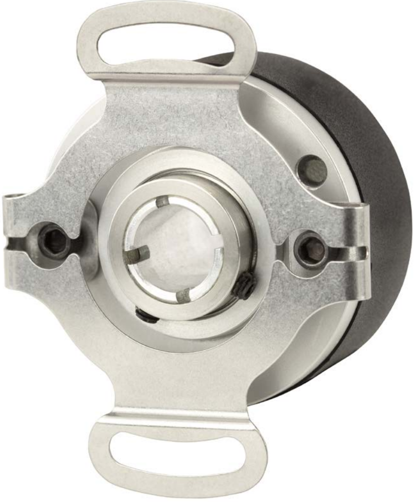
$$\text{Position in mm} = \frac{\text{Edge count}}{x \cdot N} \cdot \frac{1}{\text{PPM}}$$

$$\text{Position in inches} = \frac{\text{Edge count}}{x \cdot N} \cdot \frac{1}{\text{PPI}}$$

Where PPM = Pulses per millimeter and PPI = Pulses per inch.

MORE ABOUT INCREMENTAL-ENCODER PPR

Incremental encoders determine rotary position by generating a specific number of counts per revolution (CPRs) or pulses per revolution (PPRs) and counting those pulses as the encoder spins. The PPR rating indicates resolution, and is typically the most important factor when selecting an incremental encoder. But how should a design engineer determine what PPR is needed for a specific application? Fortunately, establishing required PPR is straightforward.

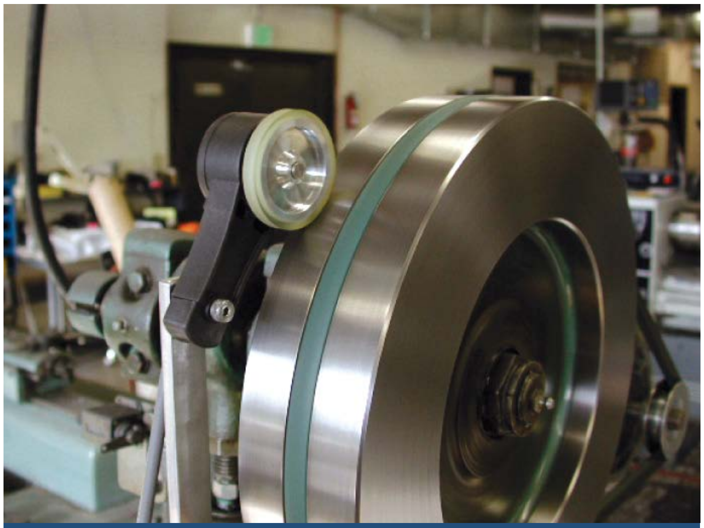


The Accu-Coder is EPC's brand of incremental encoders. The Model 15T incremental through-bore Accu-Coder encoder is a low-profile design (1.5-in. diameter) with up to 10,000 CPR and 12-pole commutation for brushless motor control. Image courtesy Encoder Products Co. (EPC)

DISTANCE OF A LINEAR AXIS BEING MONITORED

When linear motion is being measured, the required pulses per revolution is calculated by dividing the lead of the screw by the linear resolution needed for the application. Conversely, for an encoder with a given PPR, the resulting linear resolution is calculated by dividing the screw lead by the PPR. Keep in mind that if X2 or X4 encoding is being used, this should be factored into the PPR number. For example, if the desired linear resolution requires a PPR of 5,000 and X4 encoding is being used, the encoder chosen should have a PPR of 1,250 — from 5,000 divided by 4.

Wheeled encoders such as the Encoder Products Co. Model TR1 are well suited to metal-forming machines that execute extruding, profiling, and cut-to-length applications.



Measuring wheels can also yield direct feedback for another wheel in the design. In the example shown here, an Encoder Products Co. Model TR1's torsion arm allows for quick and easy installation to provide speed and direction feedback on a flywheel.

(continued)

DEEPER DIVE ON INCREMENTAL ENCODERS

$$PPR = \frac{\text{Lead}}{\text{Linear resolution}}$$

$$\text{Linear resolution} = \frac{\text{Lead}}{PPR}$$

If the travel is being measured by use of a wheel or roller, a calibration constant might be necessary, depending on the required display resolution. The calibration constant is calculated by dividing the wheel or roller circumference by the PPR of the encoder — multiplied by the gear ratio being used (if any). The result of this calculation is then multiplied by any conversion required to translate from the wheel or roller circumference units to the desired units for the display. For example, one might need to multiply by 1,000 to convert from an expression of circumference in meters to display units in millimeters.

$$K = \left(\frac{\mathrm{C}}{G \cdot N} \right)$$

Where K = calibration constant

C = Wheel or roller circumference — typically in inches or meters

G = Gear ratio

N = Incremental encoder PPR

Using a calibration constant or scaling factor has the drawback of introducing a rounding error that will accumulate over many cycles of the encoder. To avoid this, choose an encoder having a PPR that is an even multiple of the value that is being measured. For example, if one revolution of the encoder equals 12 inches, then choose a 1,200 PPR encoder.

▲

Encoders with 12-pole commutation and high temperature ratings (such as this EPC Model 260 slotted flex mount incremental encoder) are suitable for providing brushless servomotor feedback.

SPEED OF THE AXIS BEING MONITORED

Another important factor in determining the required pulses per revolution is the encoder's maximum speed — both mechanical and electrical. The mechanical speed limit is based on the maximum speed that can be obtained without causing potential damage to the encoder. The electrical speed limit is determined by the maximum frequency response of the encoder's electronics … that is, how fast the electronics can switch between on and off. The lower of the two values — mechanical speed or electrical speed — indicates the maximum speed the encoder can turn. To convert electrical speed to rpm, the frequency response is divided by PPR and multiplied by 60 (seconds per minute). Again, with X2 or X4 encoding the PPR must be multiplied by 2 or 4 respectively.

For example, consider an encoder that is rated at 100 PPR with a maximum mechanical speed of 3,000 rpm and a maximum frequency response of 100 kHz. The electrical speed is 60,000 rpm so the mechanical speed at 3,000 rpm is the limiting factor.

One final caveat: An encoder is just one part of a complete electromechanical system, so it's important to also ensure that the maximum encoder speed doesn't exceed the maximum input frequency of the device the encoder is driving.

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Where an encoder may be exposed to caustic chemicals or other harsh factory conditions, consider a stainless-steel unit with IP67 sealing. Shown here is one such Encoder Products Co. (EPC) Model 802S stainless-enclosed incremental-shaft encoder.

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DEEPER DIVE ON INCREMENTAL ENCODERS

GATED INDEX PULSE FOR INCREMENTAL ENCODERS

Incremental encoders typically use two square-wave signals in quadrature (out of phase by 90 degrees) to track position and direction of motion. But because they only track incremental position (not absolute position) they're not able to determine the true position of the motor and connected equipment after a shutdown or power loss. So most incremental encoders also include a third signal — typically referred to as the index pulse — which helps determine the actual position of the motor during startup.

The two primary signals are produced on the A and B channels, and the index pulse is produced on a third channel, commonly referred to as the Z or I channel.

Unlike the primary signals (which produce continuous square waves) the index pulse is a single pulse produced once during each shaft rotation, indicating a fixed, discrete position in the mechanical rotation (or linear movement) of the encoder. Therefore, the index pulse can be used not only to determine the position of the motor during startup, it can also be used as a counter to track the number of shaft rotations … or to reset a position counter.

The index pulse is also referred to as a marker pulse, home, or zero reference.

The index pulse in an incremental encoder can be either gated or ungated. Gating refers to whether the pulse is referenced to, or aligned with, one or both primary channels — A and/or B. An ungated index pulse typically has a length of 360 electrical degrees or larger, and the edges of the pulse have no definite correlation to either the A or B channel. A gated index pulse is truncated to either 180 or 90 electrical degrees and provides a more accurate reference position.

Index pulses that are gated to either the A or B channel have a width of 180 electrical degrees. This is referred to as half-cycle gating (with a full cycle being 360 electrical degrees). While the index pulse can be gated to either the high or the low state of the A or B channel, it is most often gated to the high state (A high or B high).

Similarly, index pulses that are gated to both the A and B channels in their high state (or to both the A and B channels in their low state) have a length of 90 electrical degrees. This is referred to as quarter-cycle gating.

Whether an index pulse is ungated, half-cycle gated, or quarter-cycle gated depends on the encoder model. And while gating improves the accuracy of the index pulse — and in turn, the home or reference position — it requires that the servo drive or controller be able to read the Z channel at a rate fast enough to detect the pulse with every revolution of the encoder.

RELATED TOPICS

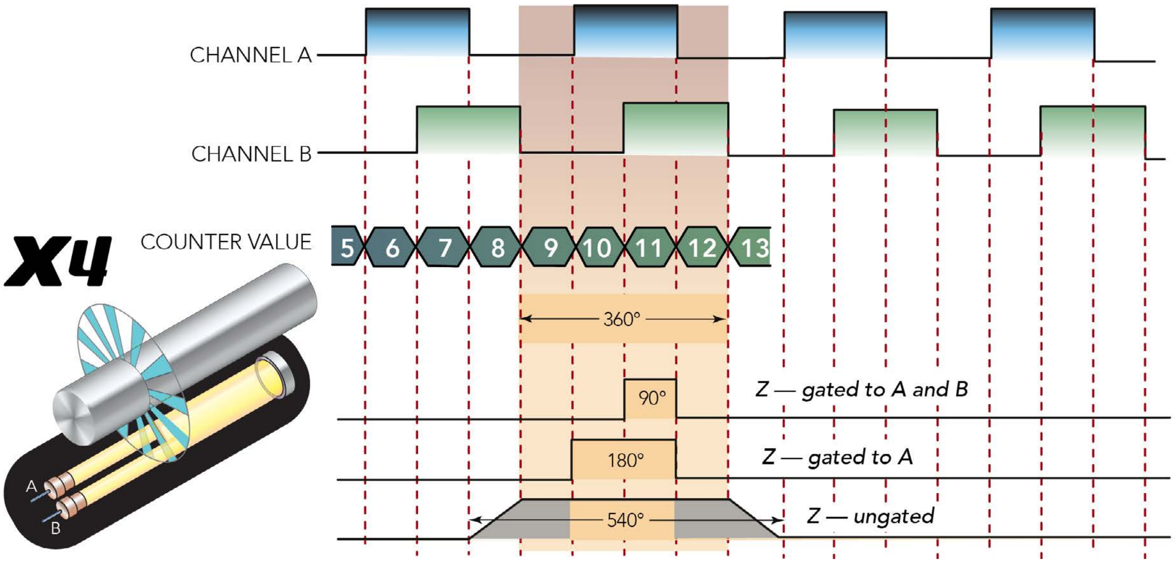
Ways to wire an incremental encoder into a motion system

Basics of encoder pull-up resistors

TTL output for incremental encoders

Why designers replace resolvers with encoders

How to use incremental encoders with stepper motors



With quarter-cycle gating, the index pulse is gated to both the A and B channels, meaning it is high for the 90° of the cycle in which both the A and B channels are high — or when both are low. With half-cycle gating, the index pulse is gated to either the A or B channel, when the channel is high or low. In this case, the index pulse width will be 180 electrical degrees.

DEEPER DIVE ON
ABSOLUTE ENCODERS

Industrial Ethernet-capable encoders such as EPC's Model A58SE (shown here) facilitate data exchange between all networked devices and maintain position information after power-off.

As we've already explored, absolute encoders yield a unique feedback result for every position and can:

- Report position even after a power interruption sans the need for homing routines
- Take the form of single-turn or multiturn versions — to satisfy short travel axis requirements or (with multiturn versions) complex or lengthy positioning routines
- Serve as position-verification devices that qualify as nonvolatile memory
- Accept programming for design flexibility — including that for point-to-point routines
- Boost safety with inherently reliable position verification (for axes run near operators)
- Resist the detrimental effects of electrical noise by avoiding error accumulation

WIRING ABSOLUTE ENCODERS INTO MOTION SYSTEMS

Absolute encoders are typically wired into motion-control systems in one of four ways — in parallel, with a serial interface, over a bus, or via an Ethernet-based protocol. Serial and bus interfaces have multiple protocols or standards … some open-source and others proprietary to specific manufacturers. The most suitable absolute-encoder connections depend on the level of application control, required resolution, required flexibility, and ease of implementation.

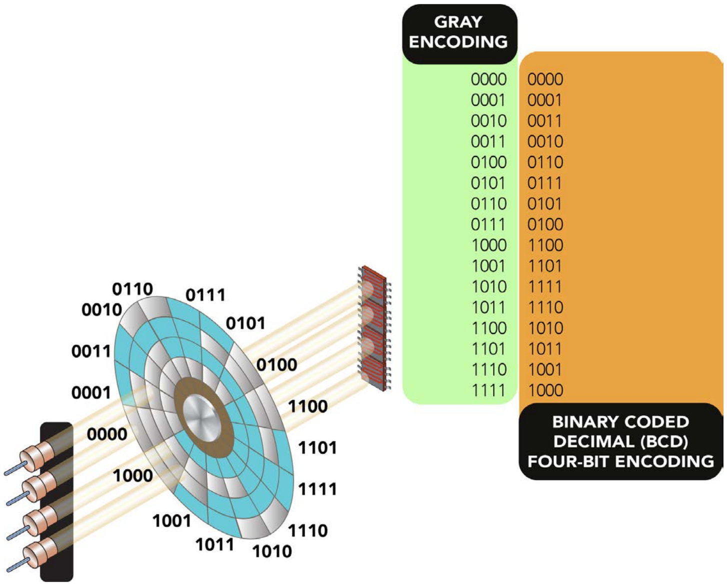
Parallel wiring: Wiring an encoder in parallel is the most straightforward method and is the standard for single-turn encoders. In parallel wiring, the encoder is connected directly to the receiving device. Each wire handles just one data bit, which means that the more bits of resolution an encoder has, the more wires are required. For high-resolution devices, this can become burdensome and costly — particularly for multiturn encoders, which have higher bits per turn and multiple turns.

Parallel wiring often provides output in a modified version of binary code, known as reflected binary code, or Gray code — named for Frank Gray, the researcher who developed it.

Consider the original alternative to Gray code: Standard binary code presents a problem for data transmission because some steps involve changes in more than one bit (digit). For example, from step three to step four a binary code changes from 0011 to 0100 — with three bits changing state. Because it's impossible for bits to change at precisely the same time, a false reading of the output could be taken.

Gray code avoids this problem by changing only one bit at each step. Because it uses one wire per bit, parallel wiring is best for simple implementations. Distance is also limited to less than 10 meters due to the potential for noise interference. That said, Gray code is a very fast communication method with all the data available in realtime — all the time.

Gray code avoids the potential for error that arises when more than one bit changes state during a given step.



GRAY ENCODING	BINARY CODED DECIMAL (BCD) FOUR-BIT ENCODING
0000	0000
0001	0001
0010	0011
0011	0010
0100	0110
0101	0111
0110	0101
0111	0100
1000	1100
1001	1101
1010	1111
1011	1110
1100	1010
1101	1011
1110	1001
1111	1000

(continued)

DEEPER DIVE ON ABSOLUTE ENCODERS

ENCODER SERIAL INTERFACES

	HIPERFACE	SSI • SINE/COS	EnDat	BiSS
CONNECTION	RS-485 bus or point-to-point • Analog point-to-point	Point-to-point	Point-to-point	Bus or point-to-point
CABLE-LENGTH COMPENSATION and ADJUSTABILITY	No	No	Yes	Yes
WIRE COUNT	8	6 to 8	6 to 12	6
HARDWARE COMPATIBLE				
OPEN PROTOCOL	No	Partially	No	Yes
ALARM • WARNING BIT	No	Definable	Yes	Definable
ANALOG SIGNALS REQUIRED	Yes	Yes	No	No
TRANSMISSION MODE	Bidirectional asynchronous	Unidirectional synchronous	Bidirectional synchronous	Bidirectional synchronous
DIGITAL TRANSMISSION RATE	38.4 kBaud	1.5 MHz	4 MHz	10 MHz

Shown here is a comparison of serial interfaces for absolute rotary encoders.

SERIAL INTERFACES FOR ABSOLUTE ENCODERS

The serial wiring scheme provides point-to-point communication from a primary control component such as a PLC or microcontroller to a secondary complementary component — which in this case is an encoder. There are several serial interfaces, with SSI (Synchronous Serial Interface) being the most common, particularly in Europe, while BiSS (Bidirectional Synchronous Serial Interface) is relatively new. EnDat is a proprietary interface developed by one encoder manufacturer; the main benefit of EnDat is that it provides for internal memory in the encoder and can carry more information than SSI.

The Encoder Products Co. (EPC) Model A58HB is a serial bus absolute encoder including SSI or CANopen communication protocol options.

Similarly, HIPERFACE is another proprietary interface that provides absolute position information at startup — and then provides incremental encoder data after that.

Both BiSS and HIPERFACE can be connected either point-to-point or via bus. Each of these interfaces, except for HIPERFACE, uses synchronous data transmission, in which the transfer of data is managed by synchronized clocks in the transmitting and receiving devices.

Serial communication is a good choice for applications with too many outputs for parallel wiring to be practical, but too few to justify a bus communication. As a benefit, serial communication works over longer distances than parallel or bus wiring schemes — sometimes more than 1,000 meters. However, because serial wiring schemes are point-to-point, there are limits to the number of nodes (devices) that can be included in a network.

BUS INTERFACES FOR ABSOLUTE ENCODERS

A bus interface lets encoders communicate with other devices on networks on a peer-to-peer basis and often takes the form of a ring topology. Two common bus protocols are DeviceNet and Profibus. Profibus was developed by the European Community and most common in Europe, while DeviceNet was developed by Allen Bradley (now part of Rockwell Automation) and is generally more common in the U.S.

Because they let multiple devices connect to a single controller, bus interfaces typically necessitate fewer cables than other wiring architectures. Bus networks also excel over longer distances — typically to 100 meters. The network topology is generally more

(continued)

DEEPER DIVE ON ABSOLUTE ENCODERS

complex (and individual bus-connectible components more expensive) than those associated with traditional connectivity arrangements. But despite the higher upfront costs, the reduction in overall cabling makes for reduced setup and troubleshooting time.

Shown here is customizable linear measurement in a heavy-duty package — the Encoder Products Co. (EPC) Model PLMS. This design works with programmable as well as bus or Ethernet-connected absolute encoder technologies — with wheel options to accommodate a range of materials.

DIFFERENCES BETWEEN SSI, BISS, HIPERFACE, AND ENDAT FOR ENCODERS

Serial communication is a simpler solution than parallel wiring (which requires a twisted pair of wires for each bit of output) and suitable for applications not complex enough to justify a fieldbus or Ethernet-based protocol. Consider the differences between the most common absolute encoder serial interfaces available today: SSI, BiSS, Hiperface DSL, and EnDat 2.2.

Synchronous serial interface or SSI: As its name suggests, SSI is a synchronous protocol — meaning that data goes from the encoder to the controller synchronously via a clock signal or pulse originating from the controller. The encoder output can be in binary or Gray code, and one bit is transmitted per clock pulse — with standard word lengths of 13 bits for single-turn encoders and 25 bits for multiturn encoders.

Synchronous serial interface uses two pairs of twisted wires for communication, per the RS-422 standard — one pair for differential data signals and one pair for differential clock signals. There are are also two wires for power to the encoder. The clock frequency, or rate of data transmission, can be up to 1.5 MHz, depending on the length of the cable. To ensure data integrity, some SSI encoders support multiple transmission — also known as *multi-path* or *ringshift* transmission — in which the same data is sent multiple times and the controller compares the transmissions to ensure they match.

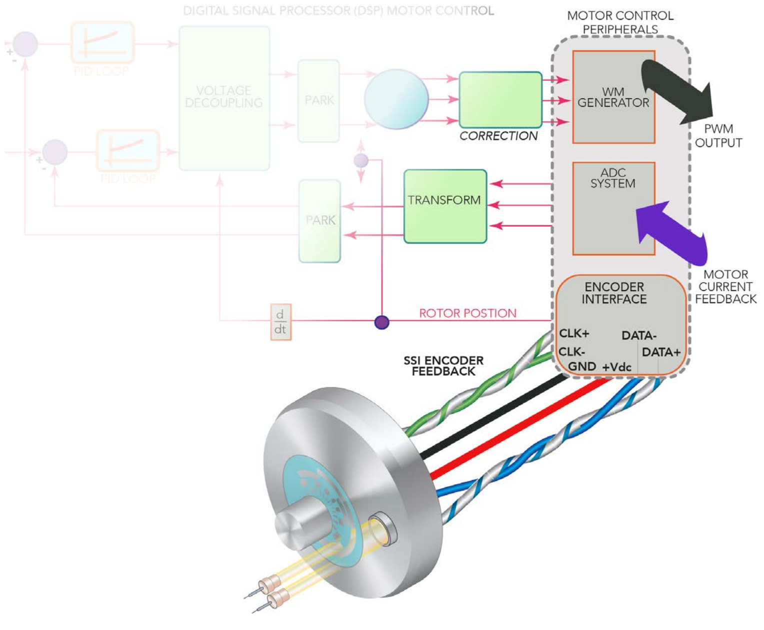
Bidirectional synchronous serial interface or BiSS: The bidirectional synchronous serial interface is an open protocol and is like SSI in that data transmission is synchronized by clock signals from the controller — but with BiSS, clock speeds up to 10 MHz are possible. BiSS also uses two twisted pairs of wires — one pair for data signals and one pair for clock signals — plus two wires for power.

Unlike SSI (which only supports unidirectional communication) BiSS supports bidirectional communication, meaning the controller can read from and write to nonvolatile memory in the encoder, where registers contain encoder identification information. BiSS encoders can also send data, such as temperature, to the controller on demand. Another unique feature of BiSS versus SSI is that within each data cycle, the primary control component determines and compensates for any transmission delay, allowing data transmission rates up to 10 Mbps.

The most current version of BiSS is BiSS-C (with C standing for continuously) although the interface is usually just called BiSS.

Unlike SSI encoders, BiSS encoders can be connected point-to-point or via bus. When connected via bus, the data from all the encoders is clocked (synchronized) to the primary control component in one continuous frame rather than individually. BiSS also implements a cyclic redundancy check (CRC) for error checking — a more reliable

The SSI encoder interface is simple, with just four wires for communication (a twisted pair for data and a twisted pair for clock signals) and two wires for power.



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DEEPER DIVE ON ABSOLUTE ENCODERS

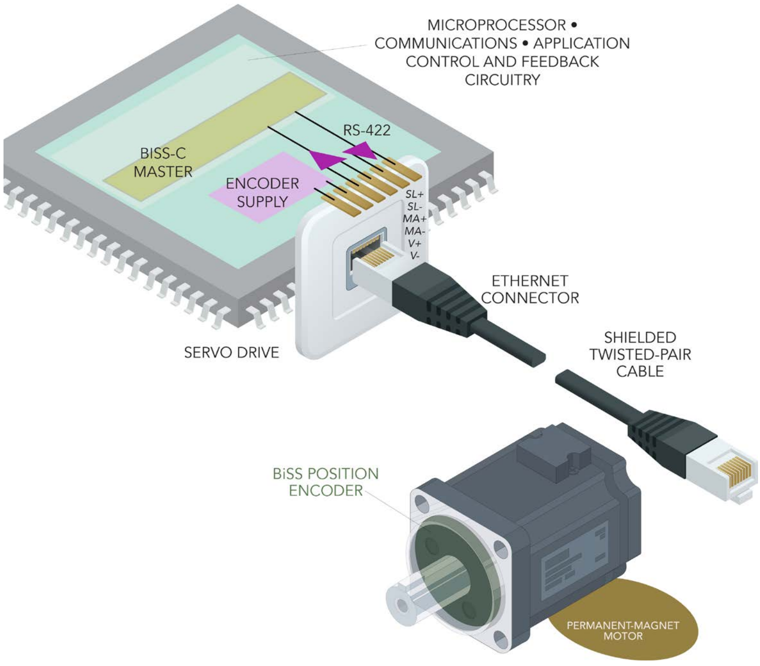
method than multiple transmission. There also exists a BiSS Safety interface for safety applications up to SIL3 per IEC 61508.

HIgh PERformance InterFACE Digital Servo Link — also called Hiperface DSL: This was originally a proprietary interface developed by SICK. However, in 2016, the interface was opened with a licensing model that lets other manufacturers integrate the technology into their product offerings.

Unlike its predecessor, Hiperface, Hiperface DSL is an all-digital protocol that uses just two wires for bi-directional communication and encoder power, bundled with the motor power cable (although a transformer is required to improve the common mode noise rejection). This gives the advantage of eliminating the need for separate encoder connections on the motor and the controller. Hiperface DSL complies with the RS-485 standard and and has a data transmission rate of 9.375 Mbaud. Data can be transmitted cyclically (as fast as possible) or synchronously with the controller clock.

The Hiperface DSL architecture also includes channels for the transfer of motor parameter data, condition monitoring data, and integrated safe motion, with data being transmitted over two digital communication wires. This redundancy and error-checking make the Hiperface DSL interface compliant with SIL3 safety standards.

Encoder Data or EnDat 2.2: This proprietary interface from Heidenhain is a synchronous, bidirectional standard that uses four wires for communication — two wires each for differential data and differential clock signals — plus two wires for power and two for either battery buffering or parallel power supply. EnDat 2.2 can provide clock frequencies of up to 2 MHz, and on some models, additional compensation for propagation delay makes frequencies up to 16 MHz possible. Because Hiperface DSL has become an open interface, EnDat is now the only serial interface for absolute encoders that remains proprietary, although it should be noted that the original Hiperface protocol also remains proprietary.



BiSS allows bidirectional communication — and so uses two wires for communication from the controller (MA+ and MA-) and two wires for communication from the encoder (SL+ and SL-) plus two wires for power.

EnDat 2.2. can also read, write, or update information stored in the encoder — and can transfer data such as sensor information or diagnostic information from the encoder to the controller. The type of data transmitted (such as absolute position, diagnostics, or parameter information) is sent via mode commands from the controller to the encoder. Like BiSS and Hiperface DSL, EnDat 2.2. is also compliant with SIL3 safety standards.

Field-programming capabilities let end users set encoder resolution, waveform, and output type — which in turn can trim costs and eliminate downtime. The Encoder Products Co. Model 25SP is one such field-programmable encoder.

ENCODERS AND EMBEDDED SMARTS FOR SIGNAL PROCESSING

Smart encoders are encoders that contain hardware and software to allow dynamic setting changes — including those to resolution and output circuit type. That can in some instances let one smart-encoder model replace various traditional encoder models.

Smart-encoder implementations abound. Some come with standard connectivity ports and networking capabilities (such as USB and EtherCAT) as well as open-source software compatibility. Others come with proprietary connectors and software designed only to work with one manufacturer's encoder. Engineers can also write software in-house as well. So the OEM must have programmers on staff or hire them to get outsourced encoder programming. While this may seem like an option to get the best-tailored

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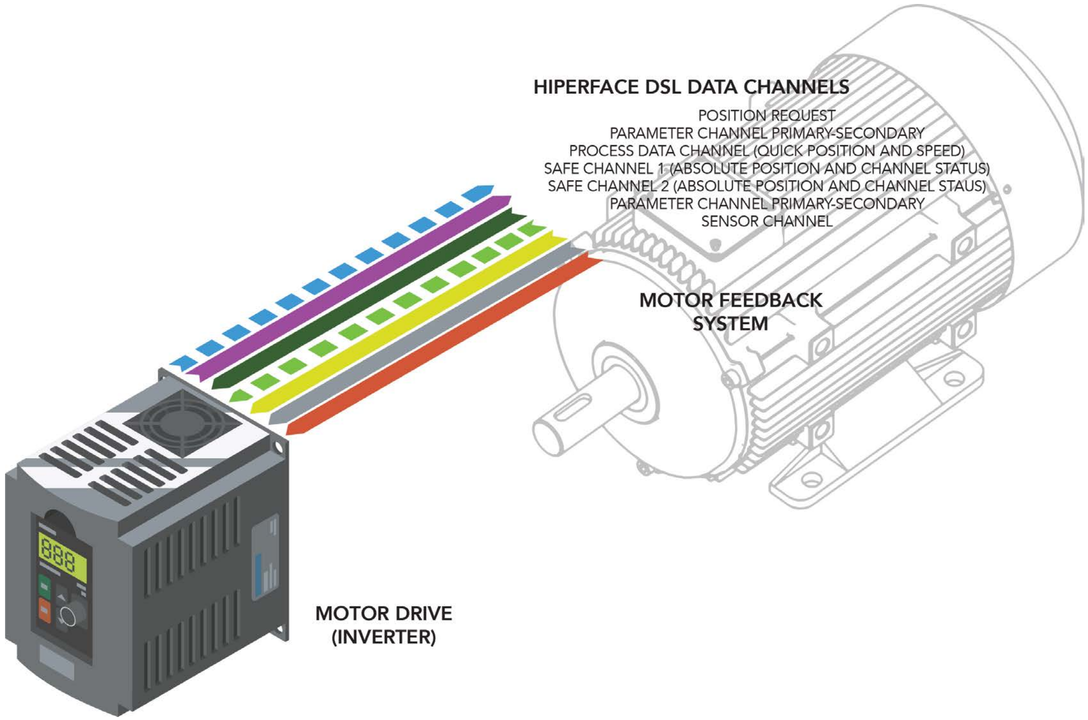
DEEPER DIVE ON ABSOLUTE ENCODERS



Hiperface DSL includes channels for position feedback, parameter exchange, process data, safe position, and condition monitoring (SensorHub) data, all transmitted on two wires which can be integrated into the motor cable.

application, keep in mind that having encoder programmers on staff or hire adds expense and design time to machine builds. That's unnecessary when off-the-shelf or manufacturer-provided software works just as well.

HOW TO CONFIGURE SMART ENCODERS

Typically, a smart encoder connects to a computer and the engineer configures the encoder through a graphical user interface (GUI) to get target settings. Then the smart encoder sends data back to the computer or other I/O system if applicable.

The ability to adjust resolution on-the-fly is especially useful because it doesn't force OEMs and end users to pick resolution right away. In contrast, manufacturers set the resolution of traditional encoders when the OEM or user orders it … so resolution is set for the life of the device.

Smart encoders allow the resolution to change at any time during operation, which boosts flexibility. It also decreases costs because OEMS don't need to buy many encoders for various resolutions — as again, one encoder can serve any number of resolutions.

Smart encoders also allow software upgrades. Both the computer software and encoder firmware are changeable by the end user. (If any faults exist in a traditional encoder, the engineer must order a replacement — causing downtime and expense.) Smart encoders can

This is the Encoder Products Co. (EPC) Model 58TP Accu-CoderPro programmable 58-mm encoder. It's available with through or blind hollow-bore options to 5/8 in. (15 mm). The version shown here has a variable BC three-point flex mount.

(continued)

DEEPER DIVE ON ABSOLUTE ENCODERS

even make use of software to solve software problems or temporarily compensate for hardware difficulties. Diagnostics let engineers proactively compensate for issues as well. Continuous encoder-health reporting minimizes downtime, as end users don't need to wait for the encoder to break before replacing it. Instead, plant personnel can monitor it with software and order replacement parts upfront — and even perform system upgrades before critical failures occur.

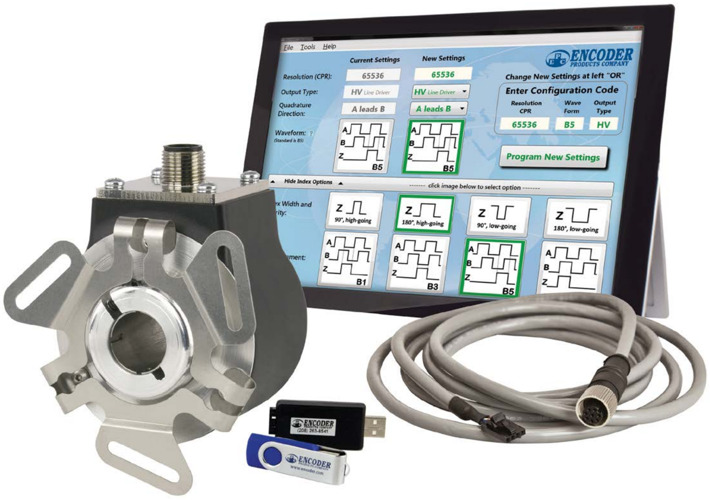
MICROPROCESSORS IN ENCODERS FOR SIGNAL PROCESSING

Embedded microprocessors in encoders offer many advantages. They improve reliability, accuracy, and responsiveness. Signal processing software running on a microprocessor can make rotation measurements that are accurate and dynamic, but with fewer moving parts than legacy encoder setups. Plus encoder microprocessors allow changes to measurement characteristics via software. That means users can tailor the encoder resolution, zero-point location, and direction settings without mechanical adjustments.

Embedded microprocessors also make encoders work as diagnostic tools. This can reduce the time it takes to get integrated designs to market — plus reduce machine downtime once the design is up and running.

Microprocessors on encoders also enable different approaches to system design and configuration. Rather than wiring everything to one computer, embedded encoder smarts allow system configuration via smartphones or web portals. Embedded microprocessors can also simplify the controller and drive system. Here, the embedded microprocessor performs various feedback and control operations; this can free up the drive system for other tasks.

Furthermore, as the IIoT spreads in industrial applications, encoder-embedded microprocessors can provide data to system and operations-level networks. These don't just send data to a drive; embedded encoder microprocessors can send data to myriad components in the system and can also be checked by any other component in the system. While this creates quite a large amount of data, the embedded microprocessor allows handling it and interpreting it without burdening the host computer or drive system. This transforms encoders from single-use components to multi-function nodes in fully integrated systems.



Shown here is an Encoder Products Co. (EPC) Model 58TP programmable encoder. Programmable encoders can save end users time and money by enabling inventory consolidation — and complementing applications requiring periodic adjustment of resolution.

MULTITURN ENCODERS

As already covered in this Design Guide, absolute rotary encoders output precise position information (even after a power-off condition) by assigning a unique digital value or word to each shaft position. But on axes with encoder-tracked rotary actuators making more than one revolution during their designed routines, there's no way to know how many turns that actuator has completed — at least not with the traditional type of rotary encoder known as a single-turn encoder. Such encoders use one code disc — and the digital position values repeat each encoder evolution. In applications for which the full range of positions doesn't exceed one revolution of the encoder, such single-turn encoders are suitable. For example, a rotary table only capable of 360° or less in either direction can use a single-turn encoder without issue.

But measuring tasks over more than one actuator or axis revolution necessitate multiturn encoders. Multiturn encoders can track the absolute position because the digital position value is not repeated until the maximum number of rotations (typically up to 4,096) is reached. Such functionality is particularly important in applications involving linear motion such as electromechanical actuators relying on rotary electric actuators that may spin many times for some small advancement of the axis's carriage or other output.

The most common multiturn encoders use multiple discs connected by gears to track the number of revolutions. The advantage of geared designs is that they eliminate the need for batteries to store position information. However, they tend to be larger than non-geared types due to the size of the gear train, and they introduce mechanical elements that can wear or break.

Another multiturn rotary encoder design uses an electronic counter with a battery backup. This technology is more compact and mechanically reliable because it doesn't contain complex gearing. The downside of encoders with battery backup is the need to periodically check and replace the battery.

A third technology found in some magnetic rotary encoders is based on the Wiegand effect. In Wiegand-based subsystems, energy is generated from the moving encoder shaft using a specially conditioned Wiegand wire that rapidly changes polarity when it encounters an alternating external magnetic field. This produces a short but strong pulse of energy in a coil wrapped around the wire. Then this energy triggers the turn counter and writes the data in nonvolatile memory. Using the Wiegand effect to track multiple encoder turns eliminates the need for batteries and additional mechanical elements. The main caveat is that because of the low energy levels produced, Wiegand-based encoder-turn tracking may be unsuitable for heavy-duty applications.

As detailed earlier in this Design Guide, position information from an absolute encoder is transmitted by parallel, serial, or bus communication. Consider the special requirements for multiturn encoders, though. Parallel communication for such encoders requires a separate wire for each bit of data, so it becomes impractical at higher resolutions, where the number of wires would be cumbersome and costly.

> Any machine-axis travel exceeding what's trackable with one encoder turn necessitates a multiturn encoder. Such applications include long linear axes and rotary axes having endless rotation — such as conveyors or rotary tables that travel only in one direction.

Because multiturn encoders can transmit 30 or more bits, they are generally above the practical limit for parallel communication — and instead communicate via fieldbus (such as Profibus) or serial (such as SSI) to simplify wiring.

WHY IS THE NUMBER 4,096 SIGNIFICANT?

A typical multiturn absolute encoder can accurately track position for up to 4,096 revolutions of the encoder wheel. So long as the number of revolutions remains less than 4,096, the encoder can provide accurate position information … but if the encoder makes more than 4,096 turns, the digital position values begin to repeat.

However, some drives and controllers offer a special type of position tracking called *modulo positioning* that can store any overflow movement (rotations or partial rotations that occur after 4,096 turns) and use this information to provide accurate positioning even beyond the maximum number of encoder turns.

SUMMARY: ENCODER POSITIONS VERSUS REVOLUTIONS

The number of steps or positions that an encoder can count in one revolution varies, but an encoder that is capable of 4,096 positions or steps per revolution is called a 12-bit encoder, because 21^2 = 4,096. So a 12-bit multiturn encoder counts 4,096 steps for each revolution — and up to 4,096 revolutions can be tracked.

Absolute rotary encoders can use either magnetic or optical sensing technology, but regardless of the technology used, what makes the encoder absolute is the way the encoder determines position. Instead of tracking pulses of light or magnetism, as an incremental encoder does, for an absolute encoder, every shaft position corresponds to a unique digital value or word. This is how the encoder knows (reads) the shaft's exact position, even after power interruption.

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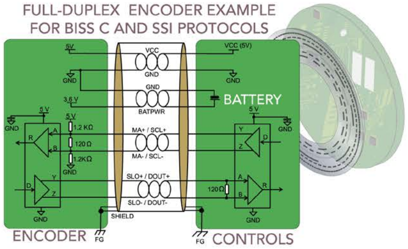
MULTITURN ENCODERS

Multiturn measuring encoders are absolute encoders that can count multiple turns. Three main technologies enable such encoder design — batteries, gearing, and self-powering setups. Batteries and gears are traditional implementations of multiturn technology; self-powering setups are newer.

MULTITURN ENCODER TECHNOLOGIES

BATTERIES FOR SIMPLICITY

Batteries maintain power supply even during machine shutdowns to keep track of multiple turns. In other words, power to the encoder is constant so all turns are tracked. The main caveat is that batteries sowly deplete and require replacement and disposal — so there's recurring maintenance and expense.

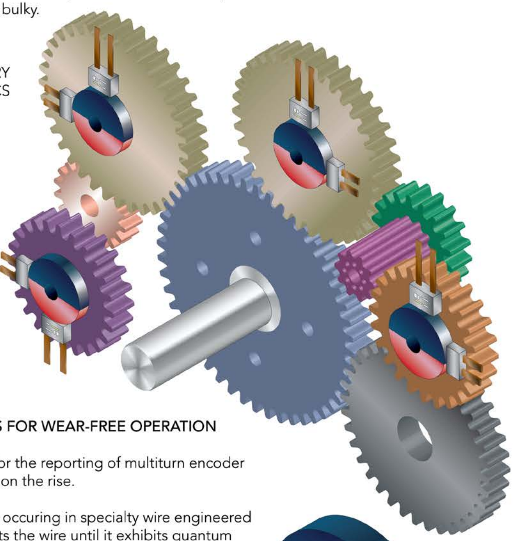


A battery is also required for the equivalent half-duplex encoder transceiver for RS-485.

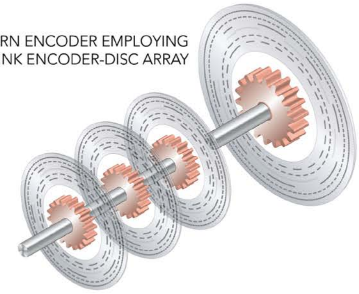
GEARS FOR PROVEN RELIABILITY

Gears are mechanical devices that allow tracking of multiple turns. One train of gears fitted with feedback can mechanically describe an encoder's unique turn count. The gear positions are tracked by optical, electric or magnetic means. Gears don't need regular replacement, but still wear out. They can also be expensive and relatively bulky.

MULTITURN ENCODER EMPLOYING GEARING TO LINK PRIMARY FEEDBACK DISC TO TURN-MONITORING SECONDARY DISCS



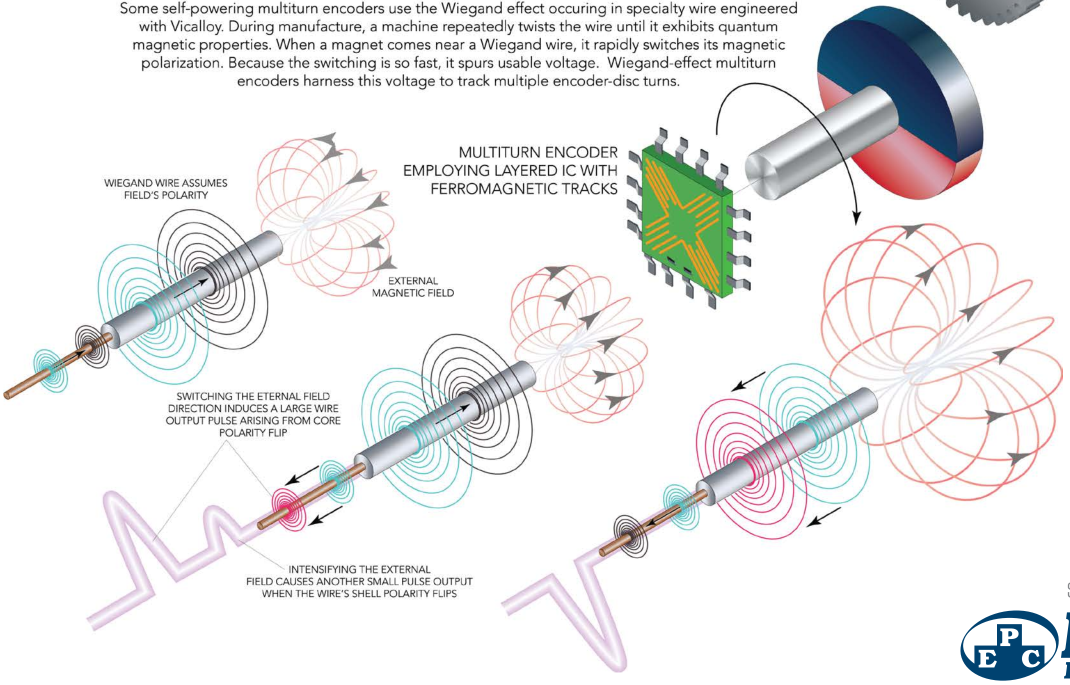
MULTITURN ENCODER EMPLOYING GEARING TO LINK ENCODER-DISC ARRAY



ENERGY-HARVESTING ELECTROMAGNETIC ELEMENTS FOR WEAR-FREE OPERATION

Electromagnetism-based energy harvesting can also be used for the reporting of multiturn encoder data. In fact, this form of operation is on the rise.

Some self-powering multiturn encoders use the Wiegand effect occuring in specialty wire engineered with Vicalloy. During manufacture, a machine repeatedly twists the wire until it exhibits quantum magnetic properties. When a magnet comes near a Wiegand wire, it rapidly switches its magnetic polarization. Because the switching is so fast, it spurs usable voltage. Wiegand-effect multiturn encoders harness this voltage to track multiple encoder-disc turns.



EPC's most popular linear measurement solution is the compact Model TR1 Tru-Trac.

LINEAR POSITION ENCODING AND THE CASE OF CAPACITIVE TECHNOLOGIES

While linear encoders are often an add-on component to a system, in many cases their benefits outweigh the additional labor and cost. For example, in ballscrew-driven applications, a lower accuracy screw can be chosen if a linear encoder is used, because the encoder feedback lets the controller compensate for positioning errors introduced by the screw.

Linear encoders bypass the mechanical linkages of rotary-to-linear motion axes to directly measure positions of loads. That avoids the effect of backlash, pitch errors, vibration problems, and the way in which heat causes expansion and geometrical distortion … which is helpful in precision designs as well as a broadening array of everyday designs.

Related: How do I pick between rotary and linear encoders?

In the past, linear encoders were reserved mostly for advanced motion-system axes sporting linear motors, as linear encoders to get high enough resolution (to 5 μm or better) were glass-scale optical types. These can be relatively costly.

Now however, new technologies based on magnetic operation or (in setups that are optical but designed to be more affordable) tape-scale designs are making linear encoders increasingly common on axes driven by rotary electric motors and ballscrews. Linear encoders with tape scales excel on long-stroke axes and applications that need easy installation. Linear-encoder variations that use magnetic operation include a linear scale that has permanent magnets or variable-reluctance strips. The read head travels with the guideway carriage with has sensors to track magnetic-field during strokes — to track position with resolutions of 25 to just a few μm in some cases.

Wheeled linear measurement solutions come in a variety of packages, with wheel options to suit a range of running surfaces. Shown here are Tru-Trac Models TR3 and TR1 — all-in-one linear-measurement solutions from Encoder Products Co.

Still more cost-effective are linear-encoder variations that use magnetic induction through a steel strip covered in grooves and raised lines that a read head tracks. Elsewhere, very simple linear encoders use a read head to track the presence and absence of ball bearings within a guideway carriage.

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LINEAR POSITION ENCODING AND THE CASE OF CAPACITIVE TECHNOLOGIES

An all-in-one encoder, measuring wheel, and spring-loaded torsion arm is a cost-effective, highly versatile way to measure linear motion. Model TR1 Tru-Trac.

Whether a linear system uses servo or stepper motors, adding a linear encoder can improve the performance of the machine and the quality of the process. In servo applications, the motor's rotary encoder monitors its speed and direction, but a linear encoder monitors the load's actual position. When stepper motors are used, position monitoring is especially important, as steppers typically run in open-loop configuration — making it difficult to unequivocally verify that the system moved to the correct position.

The first consideration when choosing a linear encoder is whether the application requires incremental or absolute feedback. Here, design engineers should consider whether they need to know the actuator's position after a power loss. If so, an absolute encoder is necessary — because an incremental encoder will lose its reference when the power supply is interrupted — requiring a rehoming sequence to determine the load's actual position.

Another way to decide whether an application requires an incremental or an absolute encoder is to consider whether rehoming is feasible after a power loss. Knowing the actuator's exact position may be noncritical, but if the travel distance is long relative to the machine's speed (as is common with machine tools) an absolute encoder can help avoid downtime and productivity due to lengthy rehoming sequences.

Related: What types of linear encoders are there and how do I choose?

Whether incremental or absolute, the next factor to consider is what technology the application requires.

The two most common types of linear encoders are optical and magnetic. Traditionally, optical scales were the sole option for feedback resolutions below 5 µm. Today, improvements in magnetic-scale technology now allow their use on axes requiring feedback resolutions down to 1µm as well.

Proper airgap is key to reliable encoder operation

Regardless of encoder type, maintaining the correct gap between the sensor and the scale is key to maintaining read accuracy. Encoders employing magnetic modes of operation can allow gaps to several millimeters; in contrast, optical encoders can necessitate airgaps to within a fraction of a millimeter. Many manufacturers publish encoder accuracy at a minimum or maximum gap value. Using the latter value ensures that even with gap-distance variability, keeping the gap below the maximum allowable value essentially guarantees the encoder will deliver its published accuracy. In most cases, actual accuracy will exceed published values.

Optical linear encoders for position tracking: Just as their rotary counterparts, optical linear encoders use a light source that shines through a linear scale and photodetectors on the scale's other side to determine position. Optical linear encoders excel on motion axes requiring sub-µm resolution. Their use of light reflection or refraction does make them unforgiving of contaminants. Plus shock loads can knock this sensor gap out of specification and even damage the encoder — especially those with glass scales or delicate sensor ASICs.

The Model TR3 Tru-Trac is an all-in-one encoder, measuring wheel, and spring-loaded torsion arm for use in heavy-duty applications such as timber processing.

Magnetic linear encoders for position tracking: Just as their rotary counterparts, magnetic linear encoders use a magnetic reader head and a magnetic scale to determine position. Consider the most common variation of magnetic linear encoders. These have a read-head sensing element that rides along a magnetically coded scale. The scale coding consists of regions of alternating polarity. These alternating north and south magnetic poles are

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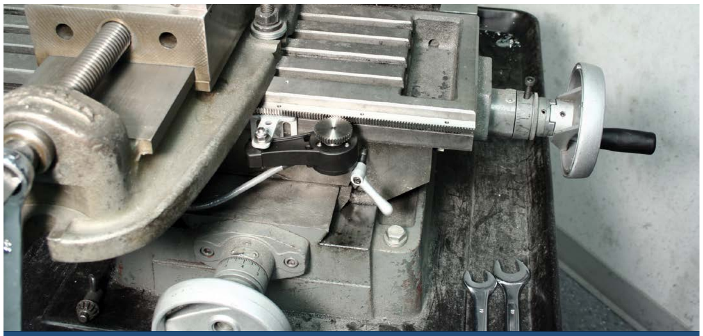
LINEAR POSITION ENCODING AND THE CASE OF CAPACITIVE TECHNOLOGIES

spaced at a precise distance called the *pole pitch*. **The read head of a magnetic linear encoder contains either Hall or magnetoresistive sensors.** These two technologies offer similar strengths and drawbacks, and in fact both quantify magnetic fields as well. However:

- Magnetoresistive linear-encoder read heads track magnetic-field direction
- Hall effect linear-encoder read heads track magnetic-field strength

As the read head moves over the tape, it detects the magnetic poles on the scale through either a change in voltage or a change in magnetic resistance.

The linear scales of magnetic linear encoders are flexible multi-layered strips having an adhesive backing and the magnetic scale — topped off (in some cases) with a plastic or stainless-steel cover strip to protect the magnetic scale. Because it's flexible and has an adhesive backing, the scale assembly is sometimes called a magnetic tape.

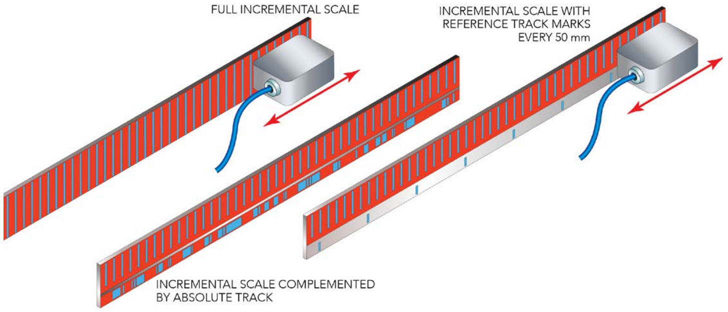


To enable precision feedback for reciprocating linear motion, the Model TR2 from Encoder Products Co. (EPC) eliminates backlash by integrating a pinion gear and rack.

Related: How do magnetic encoders work?

One advantage of magnetic linear encoders is the way in which magnetic tape can be supplied in very long lengths. In fact, real-world application examples include magnetic scales upwards of 50 meters long. But for incremental encoding, this means the homing sequence to a single reference mark could require traversing the entire length of the encoder. Therefore, magnetic linear encoders often include distance-coded reference marks. These extra marks are magnetic poles on the scale in addition to the standard magnetic poles. The reference marks are individually spaced — in other words, in a distinctive irregular pattern along the length of the tape that's independent of the standard magnetic poles.

After traversing two reference marks, linear encoders with such scales can report absolute position as well as the distance between the two marks and the direction of travel as well as the length of each magnetic pole and the basic increment — the distance between odd reference marks.



Here's one version of distance-coded encoder reference marks, where the even-numbered reference marks shift by one grating period, and any two consecutive reference marks that are detected let machine controls calculate where the reader head is along the encoder scale upon startup. To provide absolute position measurement, magnetic encoders typically employ two magnetic tracks on the same scale — an incremental track and an absolute track. Absolute track coding essentially provides the read head with a unique pattern for every position. The read head contains two sensors — one for each track. One setup uses a Hall sensor to read the absolute track — and a magnetostrictive sensor to read the incremental track. On startup, the encoder reads the absolute track to determine its position — and then during movement, it reads the incremental track for position tracking and measurement.

When repeatable back-and-forth motion occurs, a draw wire can provide linear motion feedback. The Model LCX pairs with a range of encoders to offer performance and communication protocol options.

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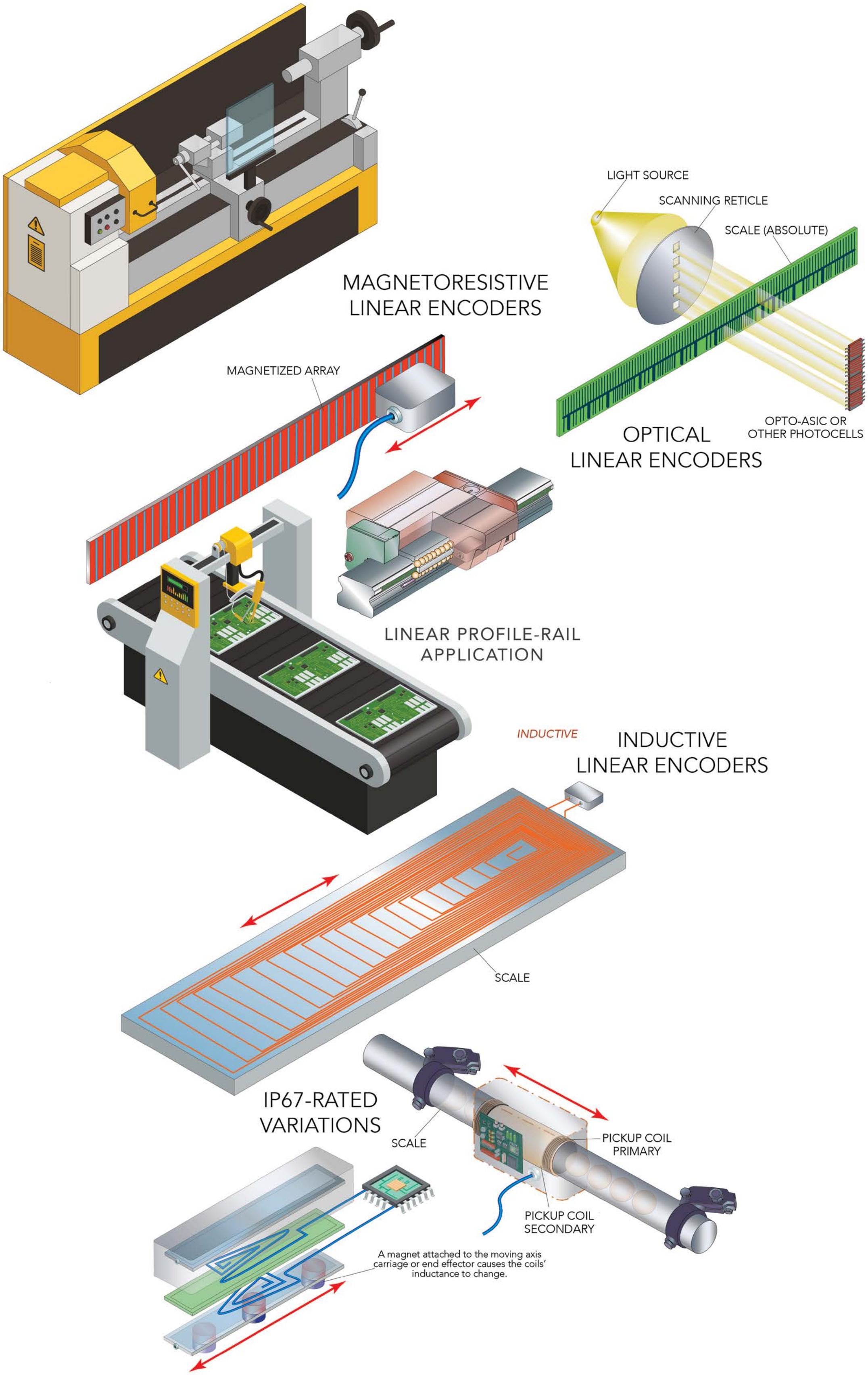
LINEAR POSITION ENCODING AND THE CASE OF CAPACITIVE TECHNOLOGIES



A magnet attached to the moving axis carriage or end effector causes the coils' inductance to change.

The most commonly used encoder technologies generally fall into three categories — optical, magnetic, and capacitive. Optical and magnetic encoders make up the bulk of the industrial automation encoder market. Not long ago, only optical technologies delivered high resolution. Now however, magnetic technologies (thanks to improvements in manufacturing and signal-processing electronics) let magnetic linear encoders *operate at high resolutions as well.*

(continued)

LINEAR POSITION ENCODING AND THE CASE OF CAPACITIVE TECHNOLOGIES

MEASURING-WHEEL ENCODERS

Linear encoder technologies can also take the form of rotary encoders combined with precision-engineered measuring wheels having precision bearings and sporting polyurethane, rubber, or knurled aluminum treads. The most suitable tread choice depends on the application's competing requirements for traction and long life. The most suitable wheel diameter depends on the axis speed and resolution requirements.

With these encoders, typically a spring-loaded wheel mount joins with an encoder shaft while allowing the wheel itself to ride a surface associated with the machine axis in question. OEMs can source such measuring wheels and assume the task of mounting them to their machines' encoder shafts — or specify fully integrated measuring-wheel encoder components. The latter offer compactness, factory-guaranteed alignment with mounting brackets, and essentially unlimited measuring distance — a key advantage over encoders relying on linear scales. They also mount in nearly any orientation.

Another advantage of measuring-wheel encoders is ruggedness: They leverage the durability of rotary encoders (that often exceeds comparable components relying on linear scales) and various bearing arrangements for high load capacity.

CAPACITIVE-BASED DISPLACEMENT TRACKING: WHERE DOES IT MAKE SENSE?

As we've explored, linear-position feedback devices classified as linear encoders typically measure travel distances ranging from a few dozen millimeters to several meters. But when a positioning system has a very short travel — a few millimeters or less — traditional linear encoders are often too bulky or don't provide the needed measuring resolution. For these applications, capacitive sensors offer a compact solution that can measure position with nanometer-level resolution.

Rather than a scale and a read head used in typical optical and magnetic linear encoders, capacitive displacement sensors are typically made from two metal plates with a dielectric or insulating layer between them — a design called a parallel-plate capacitor.

A capacitor is a device that stores electrical energy, and capacitance is a measure of how much charge the capacitor can hold. For parallel-plate capacitors, capacitance depends on three factors: the overlapping area of the plates, the permittivity of the dielectric (typically air) between them, and the distance between the plates:

$$C = \frac{\varepsilon A}{d}$$

Where C = Capacitance in farads F

ε = Permittivity of the dielectric in F/m

A = Area of overlap between the plates in m^2

d = Distance between the plates in m

When a voltage is applied to a parallel-plate capacitor, a positive charge accumulates on one plate, and a corresponding negative charge accumulates on the other plate, creating an electric field between the plates. This field is monitored for changes, which indicate a change in capacitance.

Because the dielectric separating the plates doesn't change, any change in capacitance is due to a change in geometry — either a change in the overlapping area of the plates or a change in the distance between them. Any change in the overlapping area A indicates a change in planar displacement — the movement of the plates relative to one another along parallel planes — whereas a change in the distance d indicates a change in axial displacement.

In most applications, one sensor plate is fixed (stationary) and the other plate attaches to the moving axis end effector or payload. The plates are arranged so that their overlapping area doesn't change. Therefore, any change in capacitance is a result of a change in the spacing between the plates and represents the distance that the moving object has traveled.

Linear capacitive sensors (which are also called capacitive displacement sensors in some contexts) are absolute position measuring devices. Because they directly measure the position of the moving part, linear and planar errors are eliminated — giving these linear sensors very high accuracy with resolution in the nanometer or in some cases sub-nanometer range. One example of capacitive displacement-sensor application is in optical inspection equipment, where features measured are typically at the sub-micron or nanometer level. Here, capacitive sensors ensure the correct distance is maintained between the part and measuring optics.

Because they can measure small distances and have very compact dimensions, capacitive sensors are often used in micro and nanopositioning systems based on piezomotors or voice-coil actuators. They're unsuitable for humid or wet environments or those with significant temperature changes, as water has a different dielectric constant than air and can change the permittivity ε of the capacitor.

(continued)

LINEAR POSITION ENCODING AND THE CASE OF CAPACITIVE TECHNOLOGIES

ANOTHER TECHNOLOGY: ROTARY ENCODERS EMPLOYING CAPACITANCE

Though many engineers associate capacitive encoder operation with linear varieties, rotary encoders employing capacitive-based operation also abound. These capacitive encoders offer resolution comparable to that of optical encoders with enough ruggedness for applicability in semiconductor, electronics, medical, and defense industries. They contain no LED to potentially burn out, making capacitive encoders useful where extremely long life is key. These encoders are also efficient, with current consumption typically less than 10 mA — as compared to the 20 mA or higher for traditional encoder technologies. This is especially beneficial in battery-powered applications. Two other benefits of capacitive encoders include the ability to change the encoder's resolution by modifying the line count in the electronics (without changing components) and higher resolution than most traditional magnetic encoders.

How rotary encoders based on capacitive operation work: Capacitive encoders essentially detect changes in capacitance using a high-frequency reference signal. This is via three main parts — a stationary transmitter, a rotor, and a stationary receiver. That said, capacitive encoders also come in two-part configurations with a rotor and a combined transmitter-receiver. The rotor — etched with a special pattern — rotates to modulate the transmitter's high-frequency signal.

> Capacitive encoders work by transmitting a high-frequency signal through a specially etched rotor. As the rotor moves, this etched pattern modulates the signal in a predictable way. The receiver reads the modulations, and onboard electronics translate them into increments of rotary motion.

The receiver disc reads the modulations, and onboard electronics (typically in the form of a manufacturer-proprietary ASIC) translate the modulations into increments of rotary motion. The electronics also produce quadrature signals for incremental encoding, with resolution ranging from 48 to 2,048 pulses per revolution (PPR).

In one proprietary capacitive-encoder design, the encoder has a coarse mode and a fine mode. Coarse mode is typically used upon system startup to determine initial position. The encoder then switches to fine mode for regular operation. By segmenting the total measuring range into small and equal portions, the scale of each segment can be much finer than that of encoders using one scale over the entire measuring range. This enables very high resolution without incurring undue expense.

The primary concern when using capacitive encoders is their susceptibility to noise and electrical interference. To combat this, the ASIC circuitry must be carefully designed and the algorithms for demodulation must be fine-tuned. Despite that limitation, capacitive technology has been used for many decades in digital calipers — and now increasingly common in encoders.

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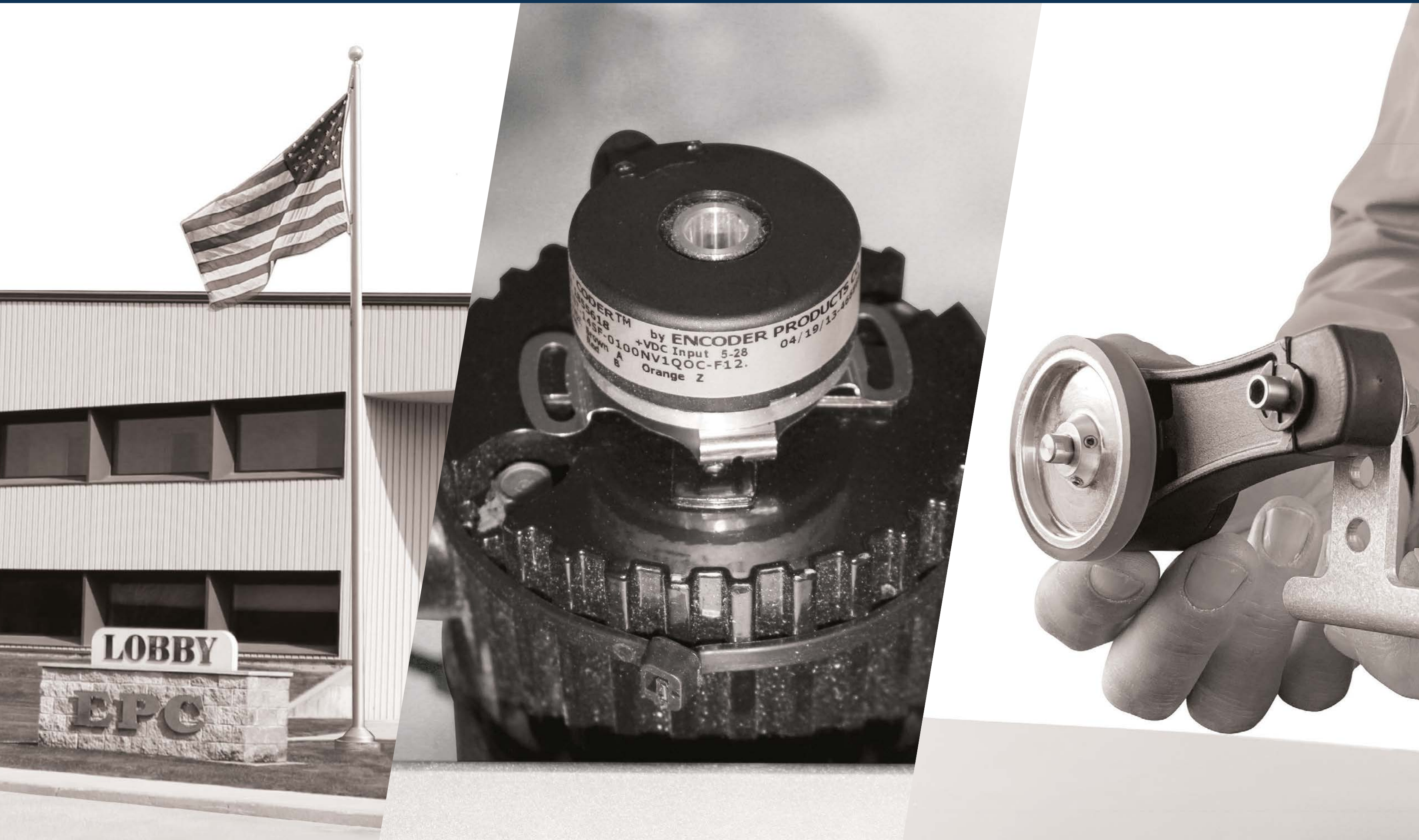
IN MOTION CONTROL



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