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Fundamentals of Industrial Encoder Sensing Technologies, Motion Detection Theory and Methods, and Signal Output Styles

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Encoders are used to determine the position, velocity and direction of a motor shaft or other mechanical motion. They provide information required for the precise control of a variety of applications, such as positioning a rotary table, pick and place, machine assembly, packaging, robotics and more. Regardless of type, all encoders provide a method of orientation detection that's used as a reference point for position control.

An encoder (for industrial controls) is a special sensor that captures position information and relays that data to other devices. The position information can be determined using one of three technologies: optical, magnetic or capacitive.

Optical encoders are the most accurate of the standard styles of encoders. When choosing an optical encoder, it's important that the encoder has extra protections built in to prevent contamination from dust, vibration and other conditions common to industrial environments.

Magnetic encoders are more rugged than optical encoders and often used in environments in which dirt, steam, vibration and other factors could interfere with optical encoder performance. Magnetic encoders cannot achieve the resolution or accuracy of optical encoders.

Capacitive encoders are relative newcomers as an industrial sensing technology. These encoders are as rugged as magnetic encoders but also do not achieve the high resolutions of optical encoders.

Regardless of the sensing technology an encoder employs, the encoder's electronics sense movement and translate that motion into industry-standard electrical signals (see "Electrical Outputs" below).

Light duty, medium duty, and heavy duty are terms to differentiate encoders by indicating how much load may be applied to the shaft.

A light duty encoder may only handle 10N (2.25 lbf) radial force on the shaft. In contrast, a heavy duty encoder may handle 100N (22.5 lbf) of radial force on the shaft. Environmental ratings also become more robust as the duty increases.
Light duty encoders are typically IP40 and IP50 (dust proof); whereas medium duty and heavy duty encoders can be rated as high as IP65 (splash proof).

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Rotary vs. Linear

There are two basic geometries for encoders: linear and rotary. Rotary and linear encoders work in similar ways. As the names imply, linear encoders measure motion along a path, and rotary encoders identify rotational motion. Thus the application determines which encoder is best suited for the job.

A linear encoder typically consists of a scale (a coded strip) and a sensing "head" that reads the spacing between the scales' coding to determine position. A linear encoder's resolution is measured in pulses per distance (pulses per inch (ppi), pulses per millimeter, etc.). The scale (coded strip) has a set resolution with marks embedded into it or on it, which is read by the head. A linear encoder with 100 ppi resolution would read 100 marks for every one inch of movement.

Unlike linear encoder resolution measurement, rotary encoder resolution is measured in pulses per revolution (PPR), also known as "line count." A rotary encoder is commonly comprised of an internal coded disc and a sensing head used to read rotary position. A linear encoder is very similar to a tape measure, while a rotary encoder is more like a measuring wheel. A rotary encoder with 100 ppr resolution would read 100 marks on its coded disc for every revolution.

Incremental vs. Absolute

Encoders come in incremental and absolute styles. Like linear and rotary encoders, incremental and absolute encoders have similarities, but they differ in wiring and movement identification.

An incremental encoder only reads pulses to provide information about the relative motion of the shaft. It has no information about location when powered up; it can only show how far the shaft has moved since the encoder was powered up. It reports back these position changes with electrical "pulses". These pulse streams can either be single channel (one output wire from the encoder) or dual channel (two wires – see also the "Quadrature" section below). Think of an incremental encoder as a tape measure with no numbers on it, only tick marks: you can tell how far you've moved, but you don't know exactly where you are unless you measure from a known spot

What Is Quadrature Output?

Quadrature output utilizes two different sets of "slots" or channels (A and B) on the optical disc inside the encoder case, separated by 90 degrees of phase shift (Image 1). These two outputs can either be ON or OFF, resulting in four different "states" for each segment of resolution. The image below shows the four different states of the quadrature output.

Time slice "a": A = OFF and B = ON
Time slice "b": A and B both OFF
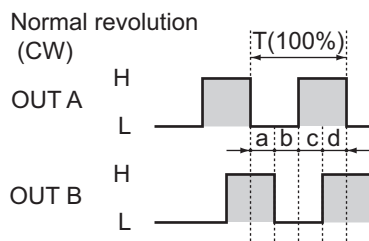Time slice "c": A = On and B = OFF
Time slice "d": A and B both ON.

Normal revolution (CW)

OUT A

OUT B

Image 1: Output Timing Diagram
The output timing diagram for a quadrature output shows A = ON, then B = ON when rotation is in a clockwise direction.

Therefore, a quadrature encoder with a resolution of 100 pulses per revolution (100 "slots" of an A channel or B channel) would actually produce 400 different states for each revolution of the encoder. That's why quadrature encoders are sometimes referred to as x4 (times 4) encoders.

The pattern of A and B turning ON and OFF also reveals which direction the encoder is turning. The encoder diagram above has A = ON, then B = ON when rotated in the clockwise direction. If this encoder were rotated counter clockwise, B would turn ON first, then A would turn ON. Encoders may differ in their definition of direction based on quadrature pattern.

Z-Pulse or the Index Channel

Certain incremental encoders have another channel called the Index Channel or Z-pulse (zero position pulse). This output pulses once per revolution of the encoder, and it's used to indicate when the encoder disc crosses the fixed zero position inside the encoder (Image 2).

The Z-pulse can be used to reset a counter, or it can be used for very precise homing. For example, consider a servo drive that uses an incremental encoder as a feedback device. The servo can home to an external signal (a proximity switch, mechanical limit switch, etc.) then proceed to the next occurrence of the encoder's Z-pulse for extremely accurate positioning.

Typically, the encoder's Z-pulse is factory set and cannot be moved. However, several families of encoders offer "servo mounting clamps" that allow the body of the encoder to be rotated, or "clocked," after installation, so the Z-pulse signal occurs in the desired position relative to a machine function.
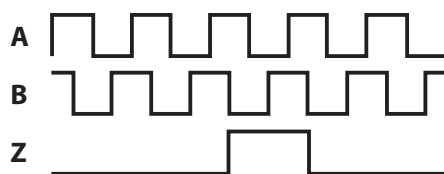
Image 2: Timing Diagram with Z-pulse shown
This timing diagram is for a 5 PPR encoder. Notice that the Z pulse stays on for one entire cycle of output B.

In contrast, a single turn, rotary, absolute encoder can report back exactly what angle it's at even when first powered up. These encoders are typically used for applications in industrial control and robotics that cannot quickly or easily perform a homing sequence. An absolute encoder is like a compass: its exact position is shown when it's viewed.

A standard absolute encoder has a resolution similar to incremental encoders (ppr, ppi, etc). Instead of an output of high-speed pulse streams, though, the output is a specified in a binary format. The maximum encoder resolution = 2^n (where n= number of output wires of the encoder). So, a 4ppr encoder has 2 outputs, an 8ppr encoder has 3 outputs, a 16ppr encoder has 4 outputs, etc. If power is lost, the actual value of the position will be known when power is restored because each location in an absolute encoder's revolution is a unique binary value.
There's one drawback to single-turn absolute encoders: the exact angle of the encoder when powered up is evident, but the number of turns made before powering up isn't. Multi-turn absolute encoders are used to solve this problem.

Multi-turn absolute encoders usually have a battery or super-capacitor that monitors how many revolutions the encoder has turned even while power is off. A multi-turn absolute encoder is like a measuring wheel that increments once per revolution. These encoders typically have serial communication and require special receivers to decode their position information.

In general, incremental encoders must be wired into high-speed inputs (although there are PPR encoders that don't produce a high-speed pulse train). Absolute encoders, however, are designed to be wired to general purpose I/O.

Gray Code

There is one more consideration when selecting single-turn absolute encoders: many don't count in standard binary code. Here is an example of the way binary normally counts up:

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Decimal #	Binary Code
12	01100
13	01101
14	01110
15	01111
16	10000
17	10001
18	10010

Notice the transition from Decimal 15 to 16: all 5 digits change state at once. If the PLC is reading inputs when this transition occurs, a bad value could temporarily be decoded by the PLC (at least for one scan) since each output may not change state at the same exact instant (there could be nanoseconds of difference).

When outputs on a machine are turned on and off based on encoder position, this could create a big problem. This may not happen very often, but considering the PLC updates its input image table with each scan (hundreds, if not thousands, of times per second), any glitch in reading position can be problematic.

To combat this problem of reading multiple transitions simultaneously, Gray Code was developed. Gray Code is a special kind of binary that only increments one bit at a time. Since only one bit changes with each transition, a PLC is much less likely to decode erroneous position data.

Decimal #	Binary Code	Gray Code
0	0000	0000
1	0001	0001
2	0010	0011
3	0011	0010
4	0100	0110
5	0101	0111
6	0110	0101
7	0111	0100

The only drawback to Gray Code is that it's not very intuitive to recognize the value as the bits change state. However, the logic to decode gray code is very straightforward and can be done with minimal ladder programming.

More details on Gray Code, universal ladder logic decoding examples and special Gray Code PLC instructions can be found at:
http://support.automationdirect.com/docs/absolute_encoders.pdf

Electrical Outputs for Incremental Encoders

Incremental encoders offer several types kinds of electrical outputs: Line Driver, NPN Open Collector, or Push-Pull (Totem Pole).

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A Line Driver output is a differential signal and requires two unique output wires per channel (Image 3). Typical wire designations are A, A- (A "not"), B, B- (B "not"), etc. When channel A is ON there's a positive voltage between A and A-. When channel A is OFF, there's a negative voltage differential between A and A-. The magnitude of the voltage differential will be greater than 2.5V. The same happens for the B and Z channels. Line Drive outputs provide a high quality signal and are fairly immune to electrical noise.

Line Driver encoders are very straightforward to wire to line driver-equipped PLC or motion controller inputs. Each output (A, B, Z) requires two wires, plus two wires for power supply (usually 5VDC).
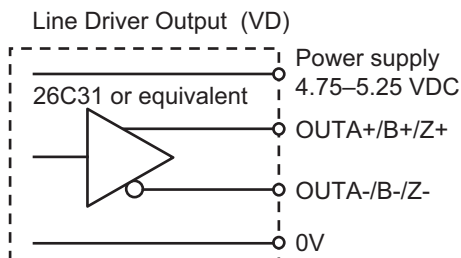
Line Driver Output (VD)

Image 3: Line Driver Output
An incremental encoder line driver output requires two unique output wires per channel, and two corresponding inputs in the automation system I/O.

A second output type is an Open Collector (NPN transistor) (Image 4). NPN Open Collector encoders "sink" current from sourcing (PNP) PLC inputs. Sinking and sourcing inputs simply refer to the current flow in a transistor.

An Open Collector encoder has A, B, Z, and 0V wires (and a wire for +DC to power the electronics). NPN Open Collector (sinking) encoders require the master PLC or motion controller to have PNP (sourcing) inputs. Open collector encoders usually accept a wide range of voltage.
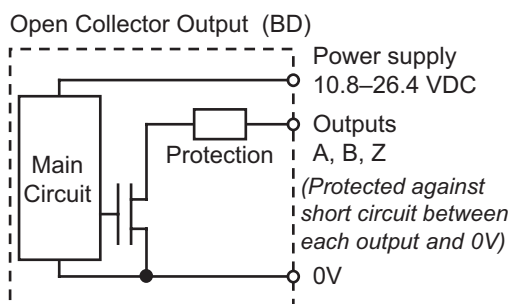
Open Collector Output (BD)

Image 4: Open Collector
An NPN (open collector) incremental encoder requires the automation system to have PNP (sourcing) inputs.

The third type of encoder output is a Push-Pull circuit, also known as a Totem Pole output (Image 5). The Push-Pull output is a special circuit that can sink or source current to the PLC. The key to this encoder's circuit is the pair of transistors in the encoder. When one transistor is ON, the other is OFF.

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If the PLC supplies current (the PLC has sourcing, or PNP inputs), the Push-Pull encoder can sink current through the lower transistor. If the PLC sinks current (the PLC has sinking or NPN inputs), the encoder will source current through the upper transistor.
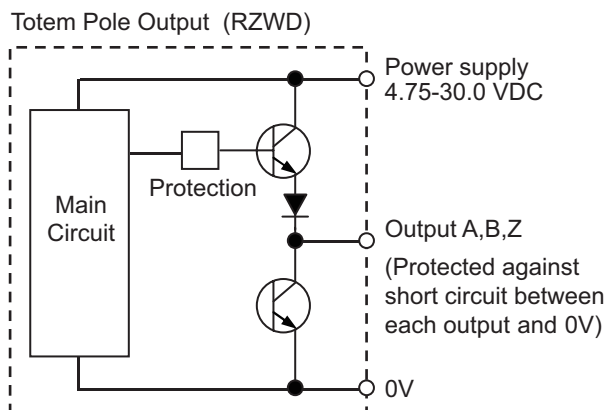
Totem Pole Output (RZWD)

Power supply
4.75-30.0 VDC

Output A,B,Z

(Protected against short circuit between each output and 0V)

0V

Main Circuit

Protection

Image 5: Totem Pole Output
An incremental encoder with totem pole output can sink or source current to the automation system.

Speed Limitations

There are two speed limitations when it comes to rotary encoders: mechanical and electrical. The mechanical speed limit is a fixed RPM value for each product, which is the maximum speed that encoder can withstand without incurring possible damage.

The electrical speed limit for each family of encoders is imposed by the maximum switching speed (frequency response) of the electronics inside the encoder. The electrical speed limit is determined by the formula: Max Electrical Speed = (Max Freq Response / pulses per revolution) x 60sec/min. The Maximum Frequency Response is a fixed number (in Hertz) for each encoder family. This is how fast the electronics can physically switch from OFF to ON. Since the Max Electrical Speed is dependent on PPR, each encoder's resolution for a given encoder family has a different Maximum Electrical Speed. For example, a 3 PPR encoder spinning at 5000 RPM produces pulses at 250Hz, while a 1000 PPR encoder spinning at 5000 PRM produces pulses at a much higher rate of 83 kHz. The 1000 PPR encoder has a much lower maximum speed than the 3 PPR encoder.

A mechanical limit on speed is typical for many encoders, but if an application requires high speed or high resolution, both the mechanical and electrical speed limits of the encoder need to be considered. The lower of the two maximum speeds is the fastest an encoder is allowed to go. For example, a certain encoder might have a Maximum Mechanical Speed of 3000 RPM. The Maximum Frequency Response (electrical speed) could be 100 kHz. Thus, the fastest speed that this encoder could spin based on the speed of the electronics is (100kHz/100 PPR) x 60s/min = 60,000 RPM, which is much higher than the mechanical limit of 3,000 RPM. This encoder should not be rotated faster than 3,000 PRM (the mechanical limit).

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While the above information is mostly geared toward incremental encoders, the same calculations hold true for absolute encoders. One extra consideration for absolute encoders is that general purpose DC inputs are not high-speed inputs, so the OFF-to-ON and ON-to-OFF response times of general purpose DC input cards may limit an absolute encoder's speed more than the encoder's switching frequency.

Summary

There are many different considerations when determining what type of encoder to use in a particular application. This article has examined some of the basic structures and types of encoders with the goal of differentiating among the various types based on encoder properties. Selecting the right encoder is not a difficult process, but it's definitely worthwhile to take time up front to ensure all the different application criteria are considered.

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