Lecture 11

Optical Sensor Systems

Common Optical Sensors

- Autocollimators
- Optical encoders
- Fiber optic sensors
- Interferometric sensors
- Laser triangulation sensors
- Vision systems
Autocollimators

Definition of Autocollimators

- Autocollimators are devices for precise measurement of small rotations around axes orthogonal to an optical sighting axis.
- Autocollimators are more often used as inspection devices than as integral parts of a sensor system for servo-controlled machines.
- Both manual and electronic autocollimators are available, although the latter are most widely used today.
- An autocollimator is actually the marriage of a collimator to a telescope.
  - A collimator takes diverging light (e.g., light from a bulb) and focuses it into a nondiverging column of light (i.e., focus the light at infinity).
A telescope, on the other hand, takes light from a source at infinity and focuses it onto a point:

thus when the angle of incidence of the light from infinity on the telescope changes, the position of the focused image on the focal plane of the telescope also changes. Because one focus of the telescope is at infinity, the axial position of the target mirror does not affect the position of the focused image.

An autocollimating telescope is an instrument that combines a collimator and telescope into a single unit.

• The measured angle is independent of the distance of the target.
Autocollimators

- The basic function of an autocollimator is to detect and measure a deviation in the position of a reference reflective surface. The autocollimator projects a collimated beam of light onto a reflective surface.
- When a deviation in the position of that reflective surface occurs, a deviated beam of collimated light returns to the autocollimator.

Applications of Autocollimators

- Autocollimators provide a last, simple method to measure straightness or flatness of a surface.
  - such as a bearing way or surface plate, a mirror mounted to a sled is incrementally moved along a straight path (linear or crisscross).
- At each incremental stop, the autocollimator is used to measure the slope from which elevations can then be derived.
- Properly used, an autocollimator can check the straightness or flatness of a surface to the $1/2-1/4 \ \mu m$ level in an order of magnitude less time than would be required to set up a laser interferometer and a straightedge.
Applications of Autocollimators

- Measures minute angle deviations
- Determines repeatability and accuracy of rotary axes
- Visible laser source allows rapid alignment

Autocollimator

The Micro-Radian TL160 laser-based autocollimator

Visual Autocollimator Sample Applications

Measurement of non-parallelism in windows, laser rod ends, and optical wedges by the two-face reflection method.

Measurement of squareness of an outside corner by aperture sharing.

Visual Autocollimator Sample Applications

Angle comparisons by aperture sharing.

Checking right angle prisms for angular and pyramid errors.
Typical Characteristics of Autocollimators

- Size: From units that can be held in the palm of your hand, to units as big as your forearm.
- Cost: In the range of $2000-$5000 for the autocollimator. Signal conditioning electronics can run from $500 to $4000.
- Measuring range: From arcseconds to a few degrees.
- Accuracy (Linearity): On the order of 0.1-0.05% of full-scale range, depending on environmental conditions. Higher accuracies can be achieved by mapping.
- Repeatability: Dependent on environmental conditions, but can be on the order of two to five times better than the accuracy.
- Resolution: Typically as small as 0.1 arcsecond but models with 0.001 arcsecond resolution are available.
- Environmental Effects on Accuracy: On the order of 1 μrad/m for a 1 °C gradient and 1 μrad/°C for the instrument itself.

- Life: The sensor is non-contact, so life is limited only by the associated electronics.
- Starting Force: The effect of the inertia of the target mirror on system dynamic performance needs to be considered.
- Allowable Operating Environment: To maintain accuracy, the system should ideally be used at 20 °C with no gradients.
- Shock Resistance: Autocollimators for military applications typically can withstand 80g shock. Precision models for aligning machinery should not be bumped around.
- Misalignment Tolerance: Misalignment results in a cosine error. For measuring straightness it is important that the step distance be kept constant and matched to the pitch of the contact areas.
- Support Electronics: Typically a black box signal conditioner for the photodiode, and a display or computer interface.
Encoders

- Encoders can be generally categorized into optical (photoelectric), magnetic encoders, and mechanical contact types.
- Photoelectric encoders in particular—due to their high accuracy, high reliability and relatively low cost, play a significant role in machine tool technology.
- The so-called scanning unit in an encoder consists of a light source, a condenser lens for collimating the light beam, the scanning reticle (標線) with the index gratings, and silicon photovoltaic cells.
- When the scale is moved relative to the scanning unit, the lines of the scale coincide alternately with the lines or spaces in the index grating.
- The periodic fluctuation of light intensity is converted by photovoltaic cells into electrical signals.
- These signals result from the averaging of a large number of lines. The output signals are two sinusoidal signals that are then interpolated or digitized as necessary.

Encoders

- Encoders are used to determine the angular position of a shaft or linear position of guideway.
- In rotary encoder, both mechanical and optical encoders are available but optical encoders are more popular. Both involve attaching an encoder disc to the shaft. The disc has lines spaced around the perimeter of the disc.
- A mechanical encoder senses the presence or absence of the lines using a conductive sensor referred to as a brush. When the brush is in contact with one of the lines a current flows through the brush and when it is not in contact no current flows.
- The optical encoder uses the lines as a mask to interrupt a beam of light as with our beam sensor.
- There are two types of encoders – incremental and absolute. An incremental encoder outputs a series of pulses as the shaft rotates. Each pulse corresponds to an increment of revolution of the shaft. The absolute encoder has several tracks that are binary coded so that the total shaft angle can be determined.
Encoders (Cont.)

- The **incremental encoder** is much simpler since it has only one track and one set of emitter/detectors or brushes. However, more burden is placed on the computer because it must keep track of the shaft position. Also, an incremental encoder usually has a second sensor to indicate an index point usually placed at the zero angle of the shaft. This is so the computer can get synchronized with the incremental pulses.

- **Direction of rotation** for incremental encoders can also be a problem since the pulsed don’t indicate direction.

- **Bidirectional incremental encoders** generally have two tracks placed so that the pulses will be 90 degrees out of phase with each other.

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Encoders (Cont.)

- The **absolute encoder** needs no synchronization or direction capability. The actual shaft position is available at all times by reading the binary coded word from each of the emitter/detectors or brushes.

- The disc of the absolute encoder has a track for each bit of the digital word representing the shaft position. The most significant bit is weighted at 180 degrees, the next bit is weighted at 90 degrees, the next bit is weighted at 45 degrees etc.

- Each track has an on area proportional to its weight. The most significant track will be on for half the circumference and off for half the circumference. The next track will be on twice and off twice at 90 degree spacings etc.
Glossary of Encoder Nomenclature

• **ACCURACY** is a measure of how close the output is to where it should be. It is usually expressed in units of distance, such as ±30 arc seconds or ±0.0001 inch. If it's expressed as a percent, make sure to state whether it's a percent of full scale (not usually meaningful with a rotary encoder) or a percent of nominal resolution.

• **BIT** is an abbreviation for Binary digit; it refers to the smallest element of resolution.

• **CPR** can mean either cycles/rev or counts/rev. To avoid confusion, this term should not be used.

**Glossary of Encoder Nomenclature**

• **ERROR** is the algebraic difference between the indicated value and the true value of the input.

• **FREQUENCY RESPONSE** is the encoder's electronic speed limit, expressed in kilohertz (1 kHz = 1000 Hz = 1000 cycles/sec). For calculations, rotational speed must be in rev/sec (rps = rpm/60); linear speed must be either in/sec or mm/sec, depending on the scale line count.
Glossary of Encoder Nomenclature

• **INDEX SIGNAL** is a once-per-rev output used to establish a reference or return to a known starting position; also called reference, marker, home, or Z.

• **INTERPOLATION** involves an electronic technique for increasing the resolution from the number of optical cycles on the disc or scale to a higher number of quadrature square waves per revolution or per unit length. These square waves can then be quadrature decoded.

• **MEASURING STEP** is the smallest resolution element; it assumes quadrature decode. (see also QUANTUM)

Glossary of Encoder Nomenclature

• **PPR** (pulses per revolution) Commonly (but mistakenly) used instead of cycles/rev when referring to quadrature square wave output.

• **QUADRATURE** refers to the 90-electrical-degree phase relationship between the A and B channels of incremental encoder output.

• **QUADRATURE DECODE** (or 4X Decode) refers to the common practice of counting all 4 quadrature states (or square wave transitions) per cycle of quadrature square waves. Thus, an encoder with 1000 cycles/rev, for example, has a resolution of 4000 counts/rev.
Glossary of Encoder Nomenclature

- **UANTIZATION ERROR** is inherent in all digital systems; it reflects the fact that you have no knowledge of how close you are to a transition. It is commonly accepted as being equal to $\pm 1/2$ bit.

- **QUANTUM** (plural is “quanta”) = BIT. It is the smallest resolution element. (Quanta and bit are more commonly used with absolute encoders; counts/rev or measuring steps are more common with incremental encoders.)

- **REPEATABILITY** is a measure of how close the output is this time to where it was last time, for input motion in the same direction. It's not usually specified explicitly, but it is included in the accuracy figure. (As a rule of thumb, the repeatability is generally around 1/10 the accuracy.)

Glossary of Encoder Nomenclature

- **RESOLUTION** is the smallest movement detectable by the encoder. It can be expressed in either electrical terms per distance (e.g., 3600 counts/rev or 100 pulses/mm) or in units of distance (e.g., 0.1° or 0.01 mm).

- **SLEW SPEED** is the maximum allowable speed from mechanical considerations. It is independent of the maximum speed dictated by frequency response.
Optical Encoders

Optical encoders typically operate on the principle of counting scale lines (slits) with the use of a light source and a photodiode.

They can be configured to measure angular rotation or linear motion.

Most optical encoders produce a digital output based on counts of scale lines and they are usually immune to electrical noise encountered by synchros, resolvers, and RVDTS (Rotary Variable Differential Transformers).

Some optical encoders also produce analog sine and cosine wave output and they may be susceptible to electrical noise.

However, unlike synchros and resolvers, optical encoders are extremely sensitive to dust, dirt, and fluid contamination and therefore must be very carefully sealed or used in a clean environment.
Operating Principle of Encoders

- In operation, a parallel beam of light produced by the light source and lens passes through four windows on the scanning reticle, through the glass scale, and onto a set of photosensors. When the scanning unit moves, the scale modulates the light beam, creating sinusoidal outputs from the photosensor.

- The four windows in the linear encoder scanning reticle are each phase shifted 90° apart. The linear encoder system combines the phase-shifted signals to produce two symmetrical sinusoidal outputs phase shifted by 90°. A fifth pattern on the scanning reticle has a random graduation that, when aligned with an identical pattern on the scale, creates a reference signal.
However, modern electronics looks not at transitions, but at changes of state. Basically, the user's electronics contains a high-speed clock and constantly samples the states of A and B. When it sees a change, it counts up or down based on the following table, where 0,1 represents the states of A and B, respectively. Instead of waiting for a triggering event from the encoder, the electronics generates its own triggering based on its detection of a state change from the encoder. A subtle difference, but critical to the operation of modern digital circuitry.

<table>
<thead>
<tr>
<th>FROM</th>
<th>TO</th>
<th>FROM</th>
<th>TO</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,1</td>
<td>1,1</td>
<td>0,1</td>
<td>0,0</td>
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<tr>
<td>1,1</td>
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<tr>
<td>0,0</td>
<td>0,1</td>
<td>0,0</td>
<td>1,0</td>
</tr>
</tbody>
</table>

**Figure 4.3.2** Using 90° out-of-phase square waves to detect direction and increase resolution by a factor of 4 using quadrature logic.
Quadrature – Pulses
(For the interested reader)

- Pulses differ from square waves in 2 important ways:
  - *Pulse widths are of fixed time duration, whereas the width of a square wave ON state is a function of speed. (of course, a function of position.)*
  - "Quadrature" has no meaning with pulse output; you get FWD pulses on one line, and REV pulses on another. (Or pulses on one line and direction information on the other.)

- Pulse output options were fairly popular at one time, but it's been dwindling for quite a while. With quad decode chips that are available, the requirement has pretty much become obsolete.

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**Quadrature**

Quad input A

Quad input A

clockwise rotation

Quad Input B

Note the change as direction is reversed

total displacement can be determined by adding/subtracting pulse counts (direction determines add/subtract)

Quad input A

counterclockwise rotation

Quad Input B

11-31
Relative Encoders

• Track position changes

Relative Encoders

• Relative position

- calibration?
- direction?
- resolution?
Relative Encoders

• Relative position

- calibration?
- direction?
- resolution?
Relative Encoders

- Relative position

Calibration?
Direction?
Resolution?

A leads B

quadrature encoding

100 lines -> ?

A diffuser tends to smooth these signals

With motors and sensors, all that's left is...
Sensor Comparison

- Incremental Encoders and Resolvers are Most Popular

<table>
<thead>
<tr>
<th>Type</th>
<th>Typical Resolution Bits</th>
<th>Incremental or Absolute</th>
<th>Signal Types</th>
<th>Signals</th>
<th>Homing Required</th>
<th>Cost</th>
<th>Electrical Immunity</th>
<th>Number of Wires</th>
<th>Electrical Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encoder Incremental</td>
<td>12</td>
<td>Incremental</td>
<td>Digital</td>
<td>A, B, Index</td>
<td>Yes</td>
<td>$</td>
<td>Very Good</td>
<td>4-8</td>
<td>None</td>
</tr>
<tr>
<td>Pseudo Absolute</td>
<td>20+</td>
<td>Absolute</td>
<td>Digital</td>
<td>A, B, or Sin Cos Coded Ref</td>
<td>Small Motion</td>
<td>$$</td>
<td>Good</td>
<td>6-10</td>
<td>Yes</td>
</tr>
<tr>
<td>Encoder Absolute</td>
<td>16</td>
<td>Absolute</td>
<td>Digital</td>
<td>Binary</td>
<td>No</td>
<td>$$$</td>
<td>Very Good</td>
<td>20+</td>
<td>None</td>
</tr>
<tr>
<td>Sinusoidal Encoders</td>
<td>20+</td>
<td>Absolute</td>
<td>Digital and Analog</td>
<td>Sin, Cos, 485</td>
<td>No</td>
<td>$</td>
<td>Good</td>
<td>6-10</td>
<td>Interpolator</td>
</tr>
<tr>
<td>Resolver</td>
<td>14</td>
<td>Absolute</td>
<td>Analog Volts RMS</td>
<td>Sin,Cos</td>
<td>No</td>
<td>$$$</td>
<td>Good</td>
<td>6</td>
<td>R/D Converter</td>
</tr>
<tr>
<td>Inductosyn</td>
<td>24</td>
<td>Incremental</td>
<td>Analog millivolts</td>
<td>Sin, Cos</td>
<td>Yes</td>
<td>$$$$</td>
<td>Fair</td>
<td>6</td>
<td>Amp +Converter</td>
</tr>
<tr>
<td>Capacitive</td>
<td>24</td>
<td>Either</td>
<td>Analog millivolts</td>
<td>Sin, Cos</td>
<td>Yes/No</td>
<td>$</td>
<td>Fair</td>
<td>6-10</td>
<td>Converter</td>
</tr>
<tr>
<td>Inductive</td>
<td>24</td>
<td>Either</td>
<td>Analog millivolts</td>
<td>Sin, Cos</td>
<td>Yes/No</td>
<td>$</td>
<td>Fair</td>
<td>6-10</td>
<td>Converter</td>
</tr>
</tbody>
</table>

Interpolation Encoders

- Output is a sine wave and a cosine wave:
  - Can be used to interpolate (typically 25X) beyond the resolution provided by the slits.
  - The resulting signal can still be used with quadrature logic to gain a 4x increase in resolution.
Interpolation Encoders

- Example, Moire fringes:

A pattern formed by the interference between two regular sets of divisions.

Moire patterns or fringes are the relatively thick lines produced when two patterns of thin lines overlap. The effect is noticeable when looking at overlapping folds in lace curtains: the comparatively fine structure of the curtains seem to have semi-regular thicker lines superimposed.

Moire Fringes
Moire Fringes

• Parallel Pattern

\[ d_m = \left| \frac{1}{d_1} - \frac{1}{d_2} \right|^{-1} \]

where

\[
\begin{align*}
    d_m &= \text{Moire fringe spacing [m]} \\
    d_1 &= \text{grating 1 spacing [m]} \\
    d_2 &= \text{grating 2 spacing [m]}
\end{align*}
\]

Source: [http://www.diracdelta.co.uk/science/source/m/o/moire%20fringes/source.html](http://www.diracdelta.co.uk/science/source/m/o/moire%20fringes/source.html)

Moire Fringes

• Rotated Pattern

\[ d_m = \frac{d}{2 \sin \left( \frac{\theta}{2} \right)} \]

where

\[
\begin{align*}
    d_m &= \text{Moire fringe spacing [m]} \\
    d &= \text{grating spacing [m]} \\
    \theta &= \text{relative rotation angle between gratings where} - \pi / 2 \leq \theta \leq \pi / 2
\end{align*}
\]

Source: [http://www.diracdelta.co.uk/science/source/m/o/moire%20fringes/source.html](http://www.diracdelta.co.uk/science/source/m/o/moire%20fringes/source.html)
Classification of Optical Encoders

• Motion Type
  ➢ Linear Type
  ➢ Rotary Type

• Reference Point
  ➢ Absolute Type
  ➢ Incremental Type

• Signal generation
  ➢ Transmitted-light Type
  ➢ Reflected-light Type

Rotary vs. Linear

• Rotary encoders are effective, low cost feedback devices that can confirm motor shaft position (or provide feedback to a servo motor).

• The accuracy of rotary encoded systems is dependent on other system components, whereas linear encoders can increase the system accuracy.

• Linear encoders tell you a stage’s position, regardless of how you got there (leadscrew errors, thermal expansion, and nut backlash, for example, are measured by a linear encoder).
Linear Encoders

• A typical linear encoder consists of a scanning unit and a scale.
• The linear encoder's scale is generally glass and is cemented to a support, usually an aluminum extrusion.
• Linear encoders also have a scanning unit, which contains a light source, photocells, and a second graduated piece of glass called the scanning reticle.
• This scanning reticle sits a short distance from the scale.

Linear Encoders

• Provide actual location feedback of a position and increase system accuracy.
• Allow a tight servo loop (when used with a linear servo motor).
  ➢ Although it is physically impossible to mount a linear encoder’s read head in the same exact place as the user’s load, it can be mounted nearby, telling you actual position (regardless of the drive mechanism accuracy). This allows correction of position in stepping motor systems.
• A rotary encoder can be used to provide damping (velocity feedback) to the position controller.
• For applications with particularly demanding accuracy requirements, laser interferometers should be considered.
Linear Encoders

- Output from an encoder can be absolute or incremental.
- Absolute encoders typically provide 10-12 bits of resolution, but 16 bit units are available.
- Incremental encoders typically provide 10-to 16-bit resolution, and ultra-high-resolution encoders can provide 21 bits of resolution (3 μ rad).

Rotary Encoders

- Provide position feedback of a rotary motor.
- Cost-effective
  - Rotary encoders provide a low cost way to confirm rotary motor position.
- Allow a tight servo loop (when used with a rotary servo motor)
  - They are an ideal feedback mechanism for use with a rotary servo motor.
  - Rotary encoders are typically mounted to the leadscrew or ballscrew shaft in the stages, which eliminates errors due to coupling wind-up and backlash, but their position feedback still depends on the accuracy of the leadscrew or ballscrew.
Signal Generation with Four-field Scanning

- A group of four windows are located on the scanning reticle. The gratings of the windows serve as scanning fields, phase-shifted from each other by one-quarter of the grating periods, and are penetrated by a parallel beam of light produced by a unit consisting of an LED and condenser lens.

- The photovoltaic cells for the incremental track produce four sinusoidal current signals, phase-shifted from each other by 90°, designated I0°, I90°, I180°, and I270°.

- The four sinusoidal signals do not at first lie symmetrically about the zero line. For this reason the photovoltaic cells are connected in a push-pull circuit, producing two 90° phase-shifted output signals I1 and I2 in symmetry with respect to the zero line.
Push-pull Circuit

- One advantage is that there's no power dissipated in the output transistors when there is no signal present.
- One disadvantage of the push-pull is the distortion of the signal near 0V.
- Distortion can be a dirty word, especially to audiophiles. However, there are ways to reduce it.

Signal Generation with Four-field Scanning

Signal generation using the imaging principle with glass scale and four-field scanning (transmitted-light method)

Signal Generation with Four-field Scanning

- The transparent index grating consists of two interlaced phase gratings with differing diffraction characteristics.
- The use of the phase grating offers two advantages:
  - This scanning method is relatively insensitive to a slight waviness of the scale tape.
  - Also, the gap and gap tolerances between the scale and scanning reticle are much greater than with the conventional scanning method.

Signal Generation with Quasi-single-field Scanning

- The index grating with one scanning field of two interlaced phase gratings generates four images on the measuring standard, with each image phase-shifted by one-quarter of the grating period.
- Since only one scanning field is used to generate all four scanning signals, fluctuations in the intensity of the light such as are caused, for example, by local contamination of the scale, have an equal effect on the four photocell signals.
- The sinusoidal output signals therefore retain a high quality even with a certain degree of contamination.
The Imaging Principle with Quasi-Single-Field Scanning

Signal generation using the imaging principle with steel scale and quasi-single-field scanning (reflected-light method)

Source: http://www.heidenhain.com/phaise2/linenc.html

The Interferential Measuring Principle with Single-field Scanning

- The interferential measuring principle exploits the diffraction of light at the grating to produce the measuring signal.
- When the scale moves, the light waves in the higher orders of diffraction undergo phase shifts that are proportional to its displacement.
- To evaluate these phase shifts, the different orders of diffraction are superposed and brought into interference.
The Interferential Measuring Principle with Single-field Scanning

Photoelectric scanning using the interferential measuring principle with one scanning field


Signal Generation with the Interferential Scanning Principle

- The scanning reticle consists of a transparent phase grating that generates and superposes the diffracted beam components.
- The scale itself is a reflection-type phase grating. Here - as with the imaging principle - the light source is a unit consisting of an LED and condenser lens.
- Interferential scanning produces at the index grating essentially three beam components with the 0, +1, and -1 orders of diffraction.
- The beam components are diffracted once again at the phase grating of the scale, at which point the zero order of diffraction is eliminated.
- The beam components of the +1, and -1 orders reflected from the scale now contain the distance information in their phase positions and are brought into interference at the index grating.
- From the resulting light modulation, the photovoltaic cells produce three 120°-phase shifted signals which are then converted to the two 90° phase-shifted signals (HEIDENHAIN).
Exposed or Sealed Linear Encoders?

- An exposed system is recommended if the environment at the machine is clean enough to ensure that there is no threat of contaminating the optical system.
- If however, the machine makes use of coolants and lubricants, or if the machine is completely encapsulated, then sealed linear encoders should be used.
Exposed or Sealed Linear Encoders?

Exposed Linear Encoders
• Higher accuracies
• Higher traversing speeds
• No friction

Sealed Linear Encoders
• Simple mounting
• Higher protection rating

Exposed Linear Encoders
• Exposed linear encoders are designed for use on machines and installations that require especially high accuracy of the measured value. Typical applications include:
  - Measuring and production equipment in the semiconductor industry
  - Component placing machines
  - Ultra-precision machines such as diamond lathes for optical components, facing lathes for magnetic storage disks, and grinding machines for ferrite components.
  - High-accuracy machine tools
  - Measuring machines and comparators, measuring microscopes, and other precision measuring devices.

Source: http://www.heidenhain.com/phaise2/linenc.html
Sealed Linear Encoders

- Sealed linear encoders are used widely on metal-cutting machine tools such as:
  - Milling machines
  - Drilling and boring machines
  - Machining centers
  - Lathes
  - Grinding machines
  - Electrical discharge machines
  - Welding machines
  - Bending presses

Simplified representation of the LS 106 Sealed Linear Encoder.

Transmission of Position Information to the Subsequent Electronics

- In addition to the actual position value, linear encoders must also supply values of the speed control loop and for commutation.
- In order to attain good dynamic performance in the drive for digital speed control, the sampling time should be kept down to 500 µs or less.
- To minimize dead time in the closed loop, the actual values for position and speed must therefore be available in the control system with the least possible delay within a few ms.
- These stringent time requirements on the transmission of position information from the encoder to the subsequent electronics can be fulfilled by incremental encoder signals with 90° phase shift either in sinusoidal or square-wave form.
- In order to attain good speed constancy with linear motors as feed drives on machine tools, one needs a resolution of 0.1 µm and finer.
Transmission of Position Information to the Subsequent Electronics

Output Signals For Incremental Rotary Encoders


Transmission of Position Information to the Subsequent Electronics

- Feed drives for machine tools are expected to attain 90 m/min, sometimes even 120 m/min. Handling equipment achieves velocities between 5 m/s and 10 m/s.
- Input frequencies of less than 1 MHz are desirable in order to be able to transmit output signals over large cable distances (>50 m) to the subsequent electronics.
- Interpolation and digitizing circuits, which up to now have been either integrated in the encoder or connected as a separate unit between the encoder and subsequent electronics, are therefore unsuited for this purpose.
- A velocity of 60 m/min and a measuring step of 0.1 µm (after 4-fold evaluation in the subsequent electronics) results with these circuits in an input frequency of 2.5 MHz.
Transmission of Position Information to the Subsequent Electronics

- For high traversing speed and small measuring steps, linear encoders with sinusoidal output signals particularly with levels of 1 Vpp at a -3dB cutoff frequency of approximately 200 kHz and more, and a permissible cable length of up to 150m are best suited for linear motors.

- Below Figure illustrates the input frequency to the subsequent electronics as a function of the signal period and of the traversing speed for linear encoders with sinusoidal output signals.

- Even with signal periods of 4 µm and a traversing velocity of 120 m/min, the frequency reaches only 500 kHz.

Transmission of Position Information to the Subsequent Electronics

- Encoders are highly subdivided in the subsequent electronics.
- The subdivision factor determines the number of steps into which one signal period is divided.
- This subdivision factor must, however, remain in a reasonable proportion to the accuracy of the linear encoder.
- A subdivision factor of 1024 and a signal period 20 μm or 4 μm results in resolutions of approximately 20 nm and 40 nm, respectively.

Transmission of Position Information to the Subsequent Electronics

- The evolving range of interferometer based encoders provide effective position feedback solutions for a broad range of precision applications. Typical applications include:
  - E-beam & laser writers
  - Mask, wafer and LCD inspection tools
  - Fiber optic alignment equipment
  - Precision machine tool and co-ordinate measuring machines
  - Long axis aerospace machine tools
Power Supply of Linear Encoders

• The permissible ripple amplitude of the stabilized dc voltage at $U_P = 5$ V is:
  - $U_{pp} < 250$ mV with $dU/dt > 5$ V/µs (high-frequency interference)
  - $U_{pp} < 100$ mV (low-frequency fundamental ripple)

Rise Characteristic of the Power Supply Voltage

Power Supply of Linear Encoders

• Voltage drop
  - The voltage drop for HEIDENHAIN cable is calculated as:
    $$\Delta U[V] = 2 \cdot 10^{-3} \cdot \frac{LC[m] \cdot I[mA]}{56 \cdot A_p[mm^2]}$$
    
    where
    
    $LC$ : Cable Length
    $I$ : Current consumption of linear encoder
    $A_p$ : Cross section of power line
Power Supply of Linear Encoders

• If a controllable power supply is not available, the voltage drop can be halved for TTL and 1 $V_{pp}$ encoders by using the sensor lines as additional power lines.

<table>
<thead>
<tr>
<th>Power Supply</th>
<th>Remarks</th>
<th>Cross section</th>
<th>Connecting cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{pp}$</td>
<td>U = 5 V ± 5% at the encoder</td>
<td>0.19 mm²</td>
<td>0.5 mm²</td>
</tr>
<tr>
<td>$V_{TTL}$</td>
<td>These voltage values apply as measured at the encoder, i.e. without cable influences. The voltage at the encoder can be monitored with the device's sensor lines.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{\mu APP}$</td>
<td>U = 5 V ± 5% at end of cable</td>
<td>0.14 mm²</td>
<td>1.0 mm²</td>
</tr>
<tr>
<td></td>
<td>These voltage values apply at the supply end for complete cable lengths up to 30 m (encoder cable and extension cable).</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Scanning Signals

Typical signal amplitude curve for sinusoidal output signals ($1V_{pp}$ or $11\mu A_{pp}$) as a function of the scanning frequency
Scanning Signals

• Signal amplitude
  ➢ For linear encoders with sinusoidal output signals, the signal amplitude is a function of the supply voltage and therefore also of the voltage drop $U$ and the cutoff frequency.

• Cutoff frequency
  ➢ For linear encoders with sinusoidal output signals: The -3dB cutoff frequency indicates the frequency at which 70% of the original signal amplitude is maintained.

Permissible Traversing Velocity

• The maximum permissible traversing velocity of an incremental linear encoder is derived from:
  ➢ the mechanically permissible traversing velocity for sealed linear encoders
  ➢ the electrically permissible traversing velocity.

• For linear encoders with sinusoidal signals the electrically permissible traversing velocity is limited by the input frequency $f_{\text{max}}$ of the subsequent electronics.

• For linear encoders with square-wave signals the electrically permissible traversing velocity is limited by
  ➢ the maximum permissible scanning frequency $f_{\text{max}}$ of the linear encoder and
  ➢ the minimum edge separation $a$ for the subsequent electronics.
Permissible Traversing Velocity

\[ V_{\text{max}} = f_{\text{max}} [\text{kHz}] \cdot SP [\mu\text{m}] \cdot 10 \cdot 60 \ [\text{seconds/min}] \]

where

- \( V_{\text{max}} \): Maximum electrically permissible traversing velocity
- \( f_{\text{max}} \): Maximum output frequency of the encoder or input frequency of the subsequent electronics
- \( SP \): Signal period of the encoder

Resultant traversing velocity as a function of the signal period and the permissible input frequency of the subsequent electronics.
Recommended Measuring Step

• The recommended measuring steps indicated in the specifications are the product of
  ➢ the period and quality of the scanning signals
  ➢ the accuracy grade of the linear encoder
  ➢ the interpolation factor of the external or integrated interpolation and digitizing electronics

Linear Encoder Accuracy

• The accuracy of linear encoders is mainly determined by:
  ➢ the accuracy of the graduation
  ➢ the interpolation error during signal processing in the incorporated or external interpolation and digitizing electronics
  ➢ the error from the scanning unit guideway along the scale.

• Linear encoder accuracy is specified in accuracy grades, which are defined as follows:
  ➢ The extreme values of the deviation $F$ with reference to their mean value lie within $\pm a \ \mu m$ for a position within any max. 1 m section of the measuring length.
Linear Encoder Accuracy

- With sealed linear encoders, this value applies to the complete encoder system including the scanning unit. This is referred to as the **system accuracy**.
- With exposed linear encoders, the above definition of the accuracy grade applies only to the scale. It is then called the **scale accuracy**.
- Poorly mounted encoders can aggravate the effect of guideway error on measuring accuracy. To keep the resulting Abbe error as small as possible, the scale or scale housing should be mounted at table height on the machine slide. It is important to ensure that the mounting surface is parallel to the machine guideway.

Rotary Encoders
Rotary Encoders

• Index pulse once per revolution – these are incremental encoders.

• Can also have absolute encoders with intricate patterns.
  Ø Expensive and rare.
  Ø Easier to just have an index to home you.

Absolute vs. Incremental Encoders

a) Incremental encoder

b) Absolute encoder
Absolute Encoders

• The absolute encoder uses a more accurate method:
  
  - *Four optical sensors are needed to detect the optical markers of the so called “grey code disc” which will be described in the following slides.*
  
  - *This four bit grey code allows the sensors to recognize 16 positions of the disc directly without a reference.*

• Not commonly used on machine tools because most have to be reset upon startup anyway.

• Moderate resolution for a price.
Absolute Encoders

- Detecting motor shaft orientation

Absolute Encoders

- Complexity of distinguishing many different states -- high resolution is expensive!
The absolute encoder that is sketched above uses four bits to encode the position of the disc.

Four light detectors are needed to determine the absolute position of the disc.

The right figure shows a simple binary scheme of encoding.

This type of encoding has the disadvantage that at the transition from 1111 to 0000 all four bits change at a time.

This may lead to decision errors when the transition is not done exactly simultaneous.

There are some ways to overcome this problem, that are shown in the next slides.
Incremental Encoders

• There are many different ways to place the markers on the encoder disc.

• A simple way is the incremental encoder that uses three optical sensors:
  
  ➢ One sensor is used to detect the reference marker (for the 0° position).
  ➢ The other two sensors are used to determine the outer markers.
  ➢ By placing them one quarter of the period out of phase the direction of the rotation can be detected.
Incremental Encoders

- Good for non-contact sensing and interfacing with computers.
- Rotary and linear encoders use circular disks with digital etching.
- Regarded as simple, reliable, accurate, and suitable for sensitive applications.
- Incremental encoders are low in cost.
- Work by using a light source interrupted by the etchings on the disk that is detected by photodetectors.
- Free advertising: US Digital for your encoder!

Gray Code

<table>
<thead>
<tr>
<th>#</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>000</td>
</tr>
<tr>
<td>1</td>
<td>001</td>
</tr>
<tr>
<td>2</td>
<td>011</td>
</tr>
<tr>
<td>3</td>
<td>010</td>
</tr>
<tr>
<td>4</td>
<td>110</td>
</tr>
<tr>
<td>5</td>
<td>111</td>
</tr>
<tr>
<td>6</td>
<td>101</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>1000</td>
</tr>
<tr>
<td>9</td>
<td>1001</td>
</tr>
</tbody>
</table>
### Gray Code

<table>
<thead>
<tr>
<th>#</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0000</td>
</tr>
<tr>
<td>1</td>
<td>0001</td>
</tr>
<tr>
<td>2</td>
<td>0010</td>
</tr>
<tr>
<td>3</td>
<td>0011</td>
</tr>
<tr>
<td>4</td>
<td>0100</td>
</tr>
<tr>
<td>5</td>
<td>0101</td>
</tr>
<tr>
<td>6</td>
<td>0110</td>
</tr>
<tr>
<td>7</td>
<td>0111</td>
</tr>
<tr>
<td>8</td>
<td>1000</td>
</tr>
<tr>
<td>9</td>
<td>1001</td>
</tr>
</tbody>
</table>
Gray Code Disc vs. Binary Code Disc

Gray code disc  Binary Code Disc

Binary (Dual) Code with V-Sampling and Gray Code

Binary Code: Advantage: absolute value at any position
Disadvantage: decision errors / improvement by V-sampling

Gray Code: Advantage: Easy and clear decision
Disadvantage: No unambiguous value at any position
Binary (Dual) Code with V-Sampling and Gray Code

• To avoid decision errors in the dual code the so-called **V-sampling** is used:

• Two lines of detectors – A and B - are placed like a “V”.

• The evaluation is done as follows:
  - If the first detector is on a “1” position, detector A₂ is taken in the second line, if it was a “0”, detector B₂ would have been taken.
  - Since A₂ is on a “0” position, in line 3 detector B is taken.
  - In general: The value “0” or “1” at the detector position in line i determines, whether detector “B” or “A” in line i+1 has to be taken.

Binary (Dual) Code with V-Sampling and Gray Code

• The **Gray code** overcomes the problem of **decision errors** not by using more detectors but by using a different coding scheme.

• In the Gray code for each transition the signal changes in only one bit at a time.

• The disadvantage is the more complex evaluation of the signals and the ambiguity of the signal at unexpected resets.
Diffraction Encoders

• With conventional encoders, slit width and hence resolution is limited by diffraction.
• Diffraction encoders use diffracted light to create interference patterns.
  ➢ These are used to generate very high resolution sine and cosine waveforms for interpolation.
  ➢ Sine and cosine waveforms are assumed to be of equal amplitude.

Diffraction Encoders

• Typical construction (Courtesy of Canon USA Inc.):

Operating principle of Canon’s laser rotary encoder.
Laser Encoders

Figure 4.3.8 Laser encoders with (left) 81,000 pulses/rev and 4 N radial, 9 N axial allowable shaft loads, and (right) 50,000 pulses/rev and 15 N radial, 19 N axial allowable shaft loads. (Courtesy of Canon USA, Inc.)

Laser Encoders

Internal construction of Canon’s laser rotary encoder.

(Courtesy of Canon USA, Inc.)
Fiber Optic Sensors

Omron's E3X-DAN incorporates a connector design that allows 16 sensors to be connected together and to share a power line, which significantly reduces wiring.


Fiber Optic Sensors

- A popular fiber optic sensor, the Fotonic sensor is a displacement sensor containing two groups of fiber optics, one set connected to a light source and termed the transmitting fibers, and the other set connected to a photo detector (photodiode) and known as the receiving fibers.
- These two groups of fibers are bundled into a common probe.
Fiber Optic Fundamentals

**Snell's Law:**
\[ n_i \sin \theta_i = n_s \sin \theta_s \]

**Total Internal Reflection:**
- The critical angle is the value of \( \theta_i \) for which \( \theta_t \) is 90°.
- \( \sin \theta_c = n_t / n_i \)
- Core higher \( n \) than cladding

**Fibers:**
- Three kinds of fibers
  a) step index multimode
  b) graded index multimode
  c) single mode


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Fiber Optic Sensors

**Interference:**
- The diagrams below illustrate the effect of light interference. When \( R_1 \) and \( R_2 \) (see previous slide) are in phase, the two signals will constructively interfere, producing a signal with a larger amplitude, as shown in Figure 1a. When \( R_1 \) and \( R_2 \) are out of phase, they will destructively interfere, making the combined signal have a smaller amplitude. This is shown in Figure 1b.
- Principles of interference are classically studied with an interferometer, such as the Michelson Interferometer of Figure 2.

Fiber Optic Sensors

- A fiber-optic sensor system consists of a fiber-optic cable connected to a remote sensor, or amplifier (see right Figure).


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Fiber Optic Sensors

- The sensor emits, receives, and converts the light energy into an electrical signal. The cable is the mechanical component that transports the light into and out of areas that are either too space constrained or too hostile back to the sensor.
- Fiber-optic cable consists of a plastic or glass core surrounded by a layer of cladding material. The difference in densities between these two components enables the cables to act in accordance with the principle of total internal reflection, which will be discussed later.

Fiber Optic Sensors

• Condition for low loss propagation of light through a fiber (Courtesy of 3M):

[Diagram showing critical angle and acceptance cone]

• Construction of a fiber optic cable and typical defects (Courtesy of 3M):

[Diagram showing fiber components and defects]

Fiber Optic Sensors

• Generalized performance characteristics for three types of reflective fiber optic probes (Courtesy of 3M):

[Graph showing reflected light intensity vs. distance]
Fiber Optic Sensors

- Referring to the schematic below, the light generated from the source is channeled through the transmitting fibers to the probe tip.
- The light then travels to the target surface and part of it is reflected back to the probe.
- A portion of the reflected light is caught by the receiving fibers and transmitted to the photo detector where its intensity is measured.
- The intensity of the reflected light is a function of distance (gap) between the probe tip and the target surface.

Source: http://www.efunda.com/designstandards/sensors/fotonic/fotonic_intro.cfm

Fiber Optic Sensors

- Bifurcate probe used in a reflective scanning mode (Courtesy of 3M):

- Typical applications of fiber optics in precision machines:
  - To carry light to or from a sensor (e.g. interferometer).
  - To carry light to and from a surface for measuring the position of the surface.
Fiber Optic Sensors

- Those who need to use a single cable assembly to both illuminate and view an object greatly benefit from the bifurcated fiber-optic cable assembly. Here, the emitter and the receiver strands are laid side by side along the length of the cable.


Benefits of Fiber Optics

- **High sensitivity:** Fiber optic sensors are extremely sensitive, being able to resolve much less than .01 psi or 1 displacements.
- **Electrical and optical multiplexing:** Multiple sensor heads can be run by one set of electronics, which can themselves be multiplexed to further expand a sensor system.
- **Immune to electromagnetic interference:** Fiber optic light is unaffected by electromagnetic interference and also shows no degradation of results when used underwater or in zero gravity.
- **Environmental ruggedness to weather and shock:** These conditions may cause "noise" but will not damage sensors.
- **Small, flexible fibers:** The optical fiber and sensing head is approximately the size of a human hair and can be configured in arbitrary shapes.
- **Market driven:** The expanding use of fiber optics by telecommunications and other industries continue to reduce the cost of key optical elements.
- **Safety:** There is no possibility of a spark, allowing its safe use even in the most hazardous sensing environments such as oil refineries, grain bins, mining operations, pharmaceutical manufacture, and chemical processing. There is also no danger of electrical shock to personnel repairing broken fibers.
**Optical Heterodyne Interferometers**

- **Michelson interferometers** count fringes which limits the resolution to about \( \frac{1}{8} \).
- **Heterodyne techniques** can be used to achieve two orders of magnitude greater resolution:

![Diagram of Optical Heterodyne Interferometer](image1)

**Optical Heterodyne Interferometers**

- **Construction of a laser head used with an Optical Heterodyne Interferometer** (Courtesy of Zygo Corp.):

![Diagram of Laser Head](image2)
Optical Heterodyne Interferometers

- One of many processes for determining optical path change using phase measurement (Courtesy of Zygo Corp.):

![Diagram of Reference channel: Acousto-optic frequency shifter and Measurement channel: Receiver]

Common-Path Heterodyne Interferometer

- A Common-Path Heterodyne Interferometer could generate a high-resolution surface-height map of a mirror surface under test. A multichannel version would be capable of sampling the surface under test in a relatively short time.

Source: [http://www.nasatech.com/Briefs/July01/NPO20786.html](http://www.nasatech.com/Briefs/July01/NPO20786.html)
Applications of Laser Measurement System

- Typical wafer stage metrology using a laser measurement system (Courtesy of Zygo Corp.):

- Linear/angular displacement interferometer (Courtesy of Zygo Corp.):
Laser Triangulation Sensors

- Typically used as non-contact displacement sensors.
- Very useful for gauging applications.

Laser Triangulation

- This type of sensor determines the position of a target by measuring the light reflected from its surface. A transmitter (laser diode) projects a light spot onto the target. The optical lens system then focuses the reflected light onto a light-sensitive device called a receiving element, which is built into the sensor head. If the target changes its position from the reference point, the position of the projected spot on the detector changes as well.
- The laser signal-conditioning electronics detect the spot position on the receiving element and coupled with linearization and additional signal processing (digital or analog) provides an output signal (digital or analog) proportional to the target position (see below Figure).
Laser Triangulation

- **Figure:** You can now accomplish precision non-contact displacement measurement with triangulation sensors. Using an optical laser sensor (Class 2), these sensors can read at a reference distance any target position change down to microns. Sensors are available that can operate at ranges from 2 to 700 mm.


Measurement Principle

- A diffused triangulation sensor projects a beam of light onto a target, and the reflected light is captured by a detector. Changes in the target height result in a corresponding change on the detector.

Photoelectric Transducers

- Opposed mode (interrupted beam) operation of a photoelectric proximity sensor:

- Retroreflective mode operation of a photoelectric proximity sensor:

- Diffuse reflection mode operation of a photoelectric proximity sensor:

- Specular reflection mode operation of a photoelectric proximity sensor:
Photoelectric Proximity Sensor

- Photoelectric proximity sensor used to control oscillating motion of a sanding machine's belt:

![Diagram of oscillating motion of rotating sanding belt](image)

Evolutions in the machine vision

- Paradigms:
  - 1965 Vision as Recognition techniques: Clustering, classification
  - 1975 Vision as Image Understanding (An AI Problem)
    - techniques: Segmentation, Knowledge representation
  - 1980 Vision as Reconstruction
    - techniques: Shape from X, World modeling
  - 1985 Active Vision
    - techniques: Kinetic depth, visual servoing
  - 1990 Vision as Process
    - techniques: Integration, Continuous operation, control
Vision Systems

- Perform well if they know what they are looking for:
  - Optical comparators.
  - Mapping the shape of a tool.
- Measuring part dimensions using structured light (After Landman):
  - Use in unstructured environments is still expensive and generally does not pertain to precision engineering applications.

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Vision Systems

- Vision systems for high speed 100% part inspection.
- Clockwise from upper left (Courtesy of Sperry Rail Inc.):
  - Sequence interruption
  - Shadowed signals
  - Transmitted signals
  - Circular scanning using reflected signals
Vision Systems

(Courtesy of Sperry Rail Inc.)