Sensor Systems

ME EN 7960 – Precision Machine Design
Topic 6

Outline

- Sensors and transducers
- Sensor performance characteristics
- Common analog output sensors
- Common digital sensors

Sensors and Transducers

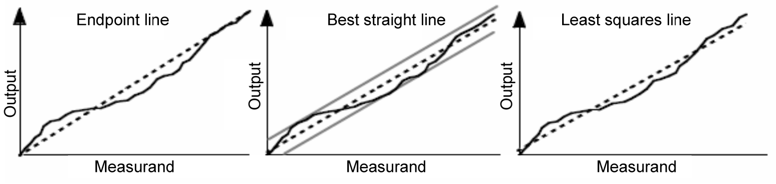
- A sensor is a device that responds to or detects a physical quantity and transmits the resulting signal to a controller
- A transducer is a sensor that converts (transduces) one form of energy to another form
- Basic types of sensors:
  - *Absolute:* The output is always relative to a fixed reference, regardless of the initial conditions
  - *Incremental:* The output is a series of binary pulses
    - Each pulse represents a change in the physical quantity by one resolution unit of the sensor
    - The pulses must be counted
  - *Analog:* The output is continuous and proportional to the physical quantity being measured
  - *Digital:* The output can only change by an incremental value given a change in the measured physical quantity

Sensor Performance Characteristics

- *Accuracy:* All sensors are accurate in that an input causes an output
  - The trick is to figure out what the sensor is saying
- *Averaged output:* Random errors can be reduced by the square root of the number of averages taken
- *Frequency Response:* is the effect of the physical quantity being measured as it varies in time, on the output of the sensor
- *Hysteresis* is the maximum difference in sensor output between measurements made from 0-100% full scale output (FSO), and 100-0% FSO

Sensor Performance Characteristics (contd.)

- *Linearity* is the variation in the constant of proportionality between the output signal and the measured physical quantity
- There are three different ways of fitting a straight line to the sensor's output versus input graph:
  - End point line
  - Best straight line
  - Least squares line



Source: Alexander Slocum, *Precision Machine Design*

Sensor Performance Characteristics (contd.)

  - The end point line connects the endpoints of the sensor's response curve
  - The best straight line is the line midway between the two parallel lines that completely envelop the sensor's response curve
  - The least squares line is the line drawn through the sensor's response curve such that the sum of the squares of the deviations from the straight line is minimized
- Mapping involves measuring the response of a sensor to a known input under known conditions
  - The results are then expressed in tabular or analytical form

Sensor Performance Characteristics (contd.)

- Most sensors' frequency responses are given in terms of the -3 db point
- If a sensor detects motion of a part and the output from the sensor used to control an axis to correct for the error:
  - The sensor should probably be operated well before its -3 db frequency response point
- The justification for this is:

Decibel (db)	Error
-0.0000087	1 ppm
-0.000087	10 ppm
-0.000869	100 ppm
-0.00869	1000 ppm
-0.087	1%
-0.915	10%
-3.0	30%

Sensor Performance Characteristics (contd.)

- The phase angle portion of the dynamic response:
  - Affects whether a sensor can be effectively used in a control system for a machine
- If there is too much lag:
  - It may not be possible for the mechanism to correct for errors sensed.
  - The error may have already irreversibly affected the process

Common Analog Output Sensors

- Capacitance sensors
- Hall effect sensors
- Inductive digital on/off proximity sensors
- Inductive distance measuring sensors
- Magnetic scales
- Magnetostrictive sensors
- Potentiometers
- Velocity sensors
- LVDT

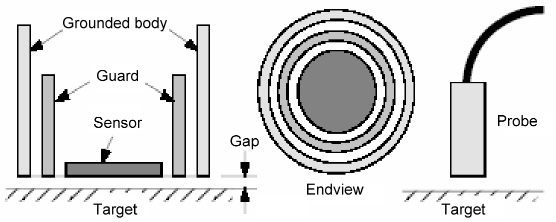
Capacitance Sensors

- Non-contact
- Requires clean, dry environment
- Resolution of 0.004% of full scale
- Bandwidth of up to 15 kHz
- Accuracy independent of target material (if conductive)
- Accuracy dependent of target material (if non-conductive)
- Target material has no minimum thickness
- Range 10 - 2000 microns (0.4 – 80 nanometer resolution @ 10 kHz)

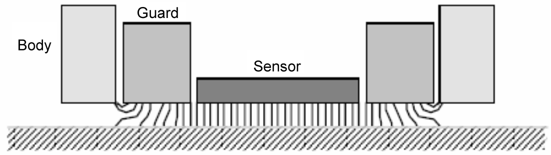
Source: Lion Precision

Capacitance Sensors

- General construction



- Field Properties

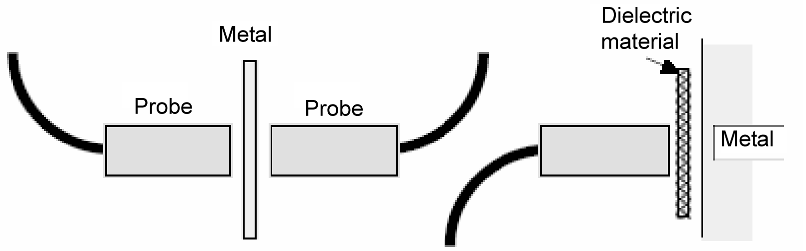


- Generally regarded as the most accurate type of analog limited range of motion sensor

Source: Alexander Slocum, *Precision Machine Design*

Capacitance Sensors (contd.)

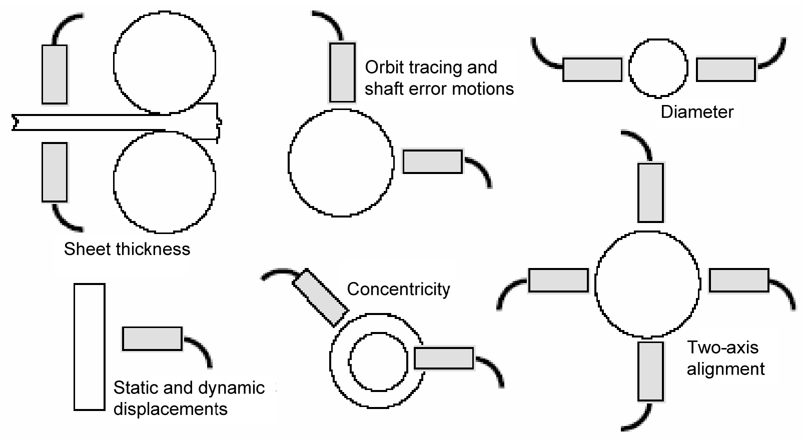
- Typical applications:
  - Position sensor for micropositioners
  - Material thickness sensing



Source: Alexander Slocum, *Precision Machine Design*

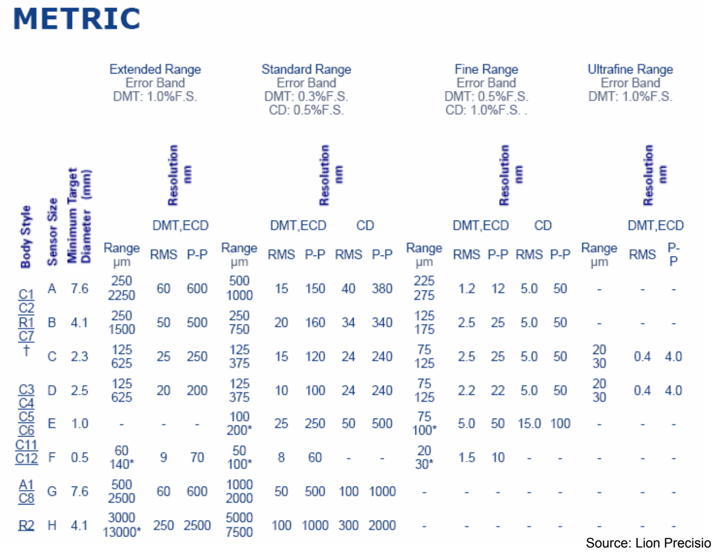
Capacitance Sensors (contd.)

– Metrology equipment (e.g. spindle error analyzers):



Source: Alexander Slocum, *Precision Machine Design*

Capacitive Sensors (contd.)



METRIC

			Extended Range Error Band DMT: 1.0%F.S.			Standard Range Error Band DMT: 0.3%F.S. CD: 0.5%F.S.					Fine Range Error Band DMT: 0.5%F.S. CD: 1.0%F.S. .					Ultrafine Range Error Band DMT: 1.0%F.S.		
				Resolution nm			Resolution nm					Resolution nm					Resolution nm	
				DMT,ECD			DMT,ECD		CD			DMT,ECD		CD			DMT,ECD	
Body Style	**Sensor Size**	**Minimum Target Diameter (mm)**	Range µm	RMS	P-P	Range µm	RMS	P-P	RMS	P-P	Range µm	RMS	P-P	RMS	P-P	Range µm	RMS	P-P
C1 C2	A	7.6	250 2250	60	600	500 1000	15	150	40	380	225 275	1.2	12	5.0	50	-	-	-
R1 C7	B	4.1	250 1500	50	500	250 750	20	160	34	340	125 175	2.5	25	5.0	50	-	-	-
†	C	2.3	125 625	25	250	125 375	15	120	24	240	75 125	2.5	25	5.0	50	20 30	0.4	4.0
C3 C4	D	2.5	125 625	20	200	125 375	10	100	24	240	75 125	2.2	22	5.0	50	20 30	0.4	4.0
C5 C6	E	1.0	-	-	-	100 200*	25	250	50	500	75 100*	5.0	50	15.0	100	-	-	-
C11 C12	F	0.5	60 140*	9	70	50 100*	8	60	-	-	20 30*	1.5	10	-	-	-	-	-
A1 C8	G	7.6	500 2500	60	600	1000 2000	50	500	100	1000	-	-	-	-	-	-	-	-
R2	H	4.1	3000 13000*	250	2500	5000 7500	100	1000	300	2000	-	-	-	-	-	-	-	-

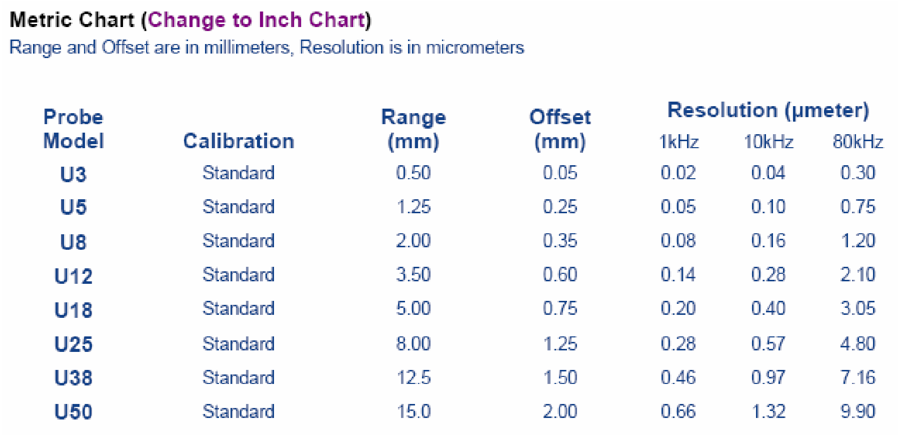
Source: Lion Precision

Inductive Probes

- Use the principle of Eddy currents for sensing distance
- Non-contact.
- Resolution 0.008% of full scale
- Bandwidth up to 80 kHz
- Very sensitive to material properties (ferrous vs. non-ferrous)
- Insensitive to environment
- Target material must be conductive
- Target must have minimum thickness (0.01 – 1.6mm)
- Range 500 – 15,000 microns (resolution 0.04 – 1.2 microns)

Source: Lion Precision

Inductive Probes



Metric Chart (Change to Inch Chart)

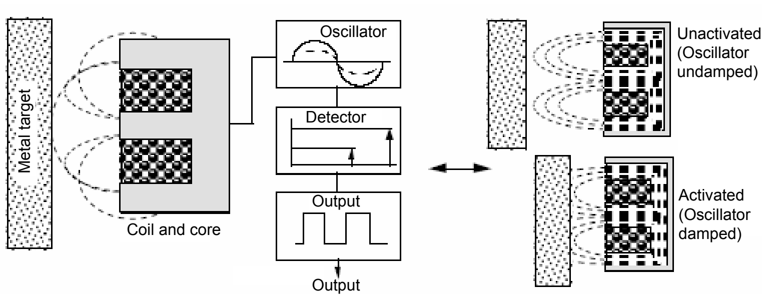
Range and Offset are in millimeters, Resolution is in micrometers

Probe Model	Calibration	Range (mm)	Offset (mm)	Resolution (µmeter) 1kHz	10kHz	80kHz
U3	Standard	0.50	0.05	0.02	0.04	0.30
U5	Standard	1.25	0.25	0.05	0.10	0.75
U8	Standard	2.00	0.35	0.08	0.16	1.20
U12	Standard	3.50	0.60	0.14	0.28	2.10
U18	Standard	5.00	0.75	0.20	0.40	3.05
U25	Standard	8.00	1.25	0.28	0.57	4.80
U38	Standard	12.5	1.50	0.46	0.97	7.16
U50	Standard	15.0	2.00	0.66	1.32	9.90

Source: Lion Precision

Inductive Digital On/Off Proximity Sensors

- General operating principle (Courtesy of Turck Inc.):

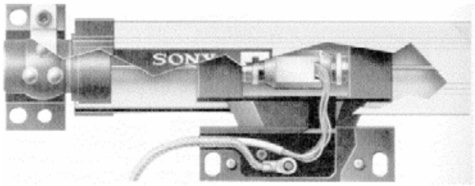


Source: Alexander Slocum, *Precision Machine Design*

- Typical applications:
  - Industrial limit switches
  - "Coarse" home position sensor for machine tools (fine home position via encoder home pulse)

Magnetic Scales

- Operates on same principle that allows a disk drive to locate stored information
- More robust than linear optical encoders
- Magnetically encoded linear scale and sliding read head (Courtesy of Sony Magnescale Inc.):

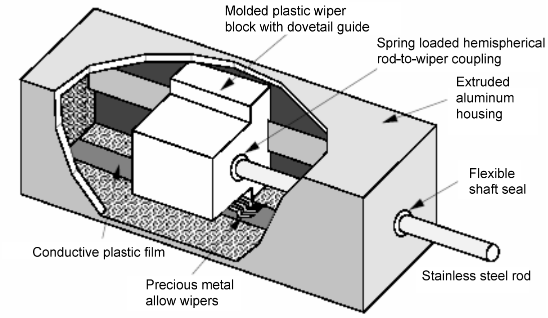


- Becoming more and more common sensor for measuring linear motion of machine tool axes

Source: Alexander Slocum, *Precision Machine Design*

Potentiometers

- General operating principle (Courtesy of Vernitech Corp.):



- Typical applications:
  - As a sensor in a high reliability all analog servo system
  - Short range of motion servo systems

Source: Alexander Slocum, *Precision Machine Design*

Linear Variable Displacement Transducers (LVDT)

- DC-operated ("DC-to-DC") LVDT's are easy to install and require little signal conditioning, and relatively inexpensive
- AC-operated LVDT's are generally smaller in body size and more accurate than DC versions
  - They will also normally operate at higher temperatures
- Range 1 – 940 mm (accuracy 0.25 – 235 microns)
- Submersible (some models)

Source: Sensotec

Velocity Sensors

- Linear velocity sensors tend to act like antennas, so they pick up EMI easily; thus their use should be avoided
- Rotary velocity sensors (tachometers) are essentially driven DC motors
- Typical applications:
  - Speed control
  - Analog velocity feedback

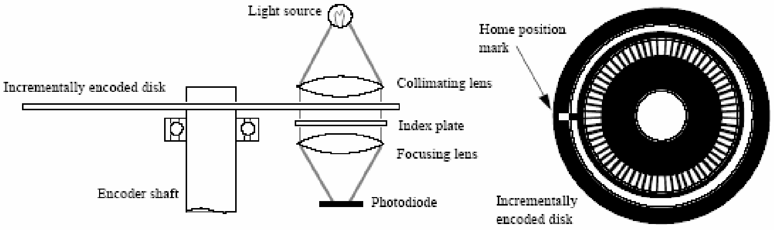
Common Optical Sensors

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

Optical Encoders

- Common types:
  - Incremental position encoders
  - Interpolation (E.G., Moire fringe) encoders
  - Absolute position encoders
  - Diffraction encoders
  - Quadrature logic
  - Typical characteristics of optical encoders

Incremental Position Encoders



Source: Alexander Slocum, *Precision Machine Design*

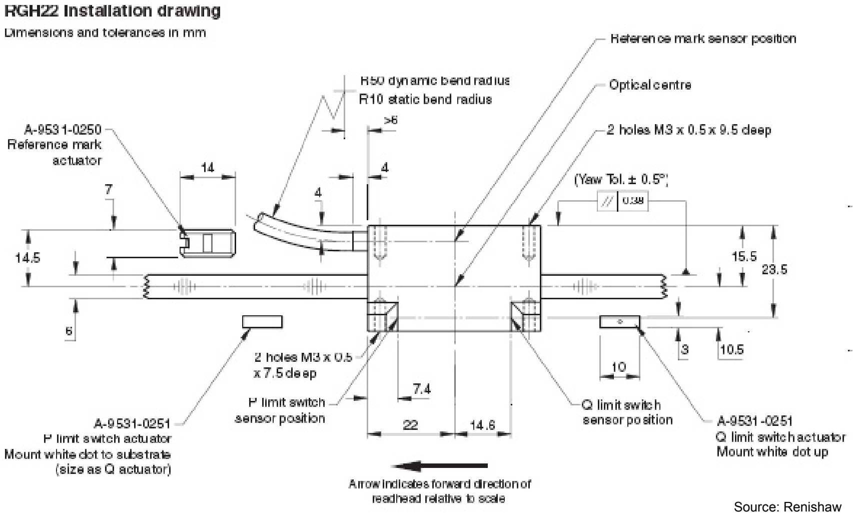
- Most commonly used type
- Reasonable resolution
- Inexpensive and widely available
- Quality is typically proportional to price
  - Poor gratings and poor electronics lead to output signal orthogonality errors
  - Quadrature signals are 90°±N°, which cause velocity calculation errors in control loops

Optical Encoder (Renishaw)

Source: Renishaw

- Non-contact
- No enclosure
- Resolution 50 nm – 5 microns
- Built-in interpolation
  - Robust against EMF
- Built-in limit and reference switch
- Uses flexible, self-adhesive 20 micron tape
- Maximum speed 10 – 3 m/s
- $800-1000 for read head, $450 for tape (3m)

Optical Encoder (Renishaw)



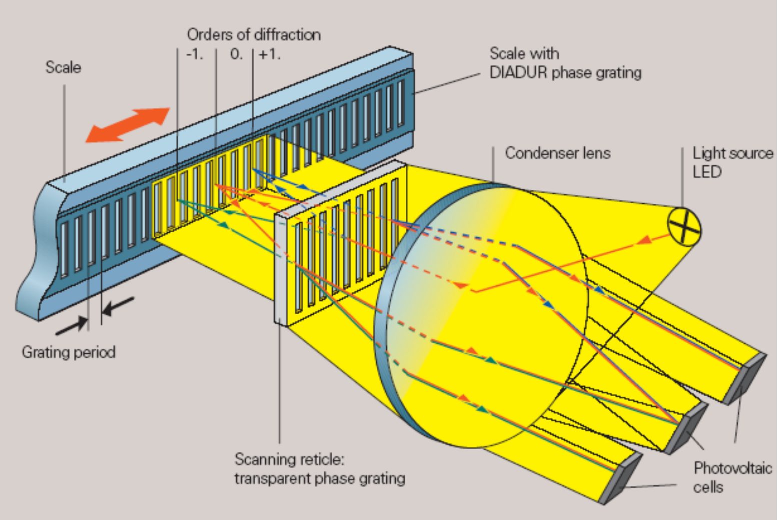
Source: Renishaw

Diffraction Encoders

- The interferential scanning principle exploits the diffraction and interference of light on a fine graduation to produce signals used to measure displacement
- A step grating is used as the measuring standard: reflective lines 0.2 µm high are applied to a flat, reflective surface
- In front of that is the scanning reticle—a transparent phase grating with the same grating period as the scale
- When a light wave passes through the scanning reticle, it is diffracted into three partial waves of the orders –1, 0, and +1, with approximately equal luminous intensity
  - The waves are diffracted by the scale such that most of the luminous intensity is found in the reflected diffraction orders +1 and –1
- These partial waves meet again at the phase grating of the scanning reticle where they are diffracted again and interfere
- This produces essentially three waves that leave the scanning reticle at different angles
- Photovoltaic cells convert this alternating light intensity into electrical signals

Source: Heidenhain

Diffraction Principle



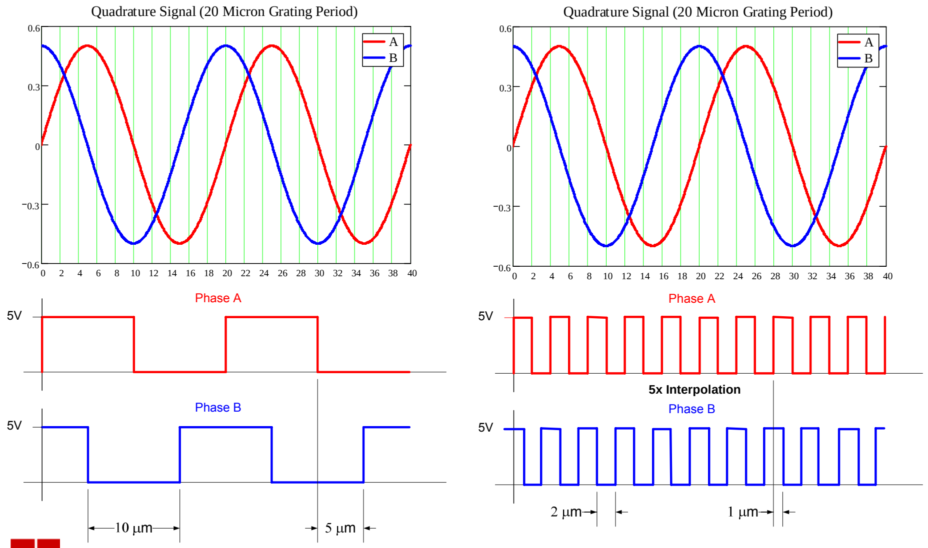
Source: Heidenhain

Optical Encoder (Heidenhain)

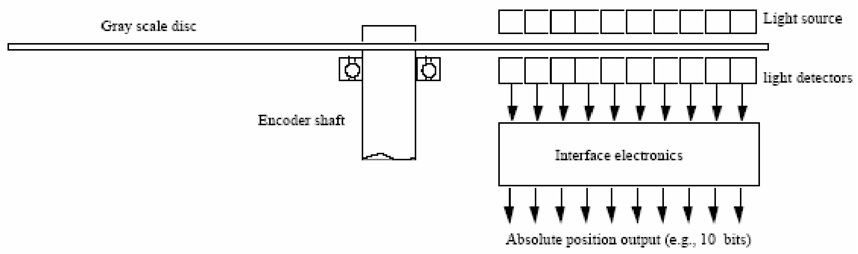
- Non-contact
- No enclosure
- 70 – 270 mm measuring length
- 0.001 micron resolution
- Accuracy ± 0.5 µm
- Glass scale

Source: Heidenhain

Quadrature Encoder (20 μm Grating Period)



Absolute Position Encoder

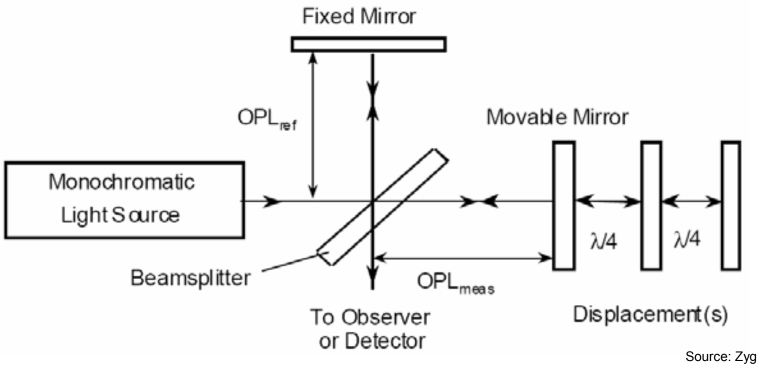


Source: Alexander Slocum, *Precision Machine Design*

- Not commonly used on machine tools because most have to be reset upon startup anyway
- Moderate resolution for a price

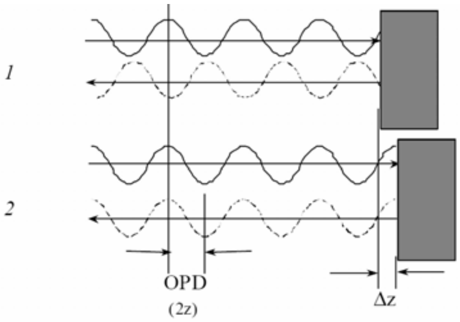
Interferometers

- Michelson interferometers count fringes which limits the resolution to about λ/8
- Heterodyne techniques can be used to achieve two orders of magnitude greater resolution:



Source: Zygo

Principle of Interferometers

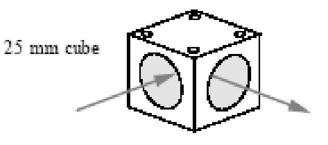


- **Scenario 1:** The incoming and the reflected beam are shifted by 180 degrees -> intensities cancel each other
- **Scenario 2:** The incoming and reflected beam are in phase -> intensities add up
- When two waves interfere, the independent electric (E) fields sum to generate a net E field
  - The Intensity (I) is equal to the square net E field
- If waves intersect in phase, totally constructive interference occurs
  - This is the condition of maximum brightness
- When the waves are 180° out of phase, totally destructive interference occurs
  - This is the condition of complete extinction.
- When the target is displaced by half of the wavelength, the intensity goes through exactly one period
  - This corresponds to a light-dark-light transition

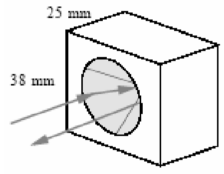
Source: Zygo

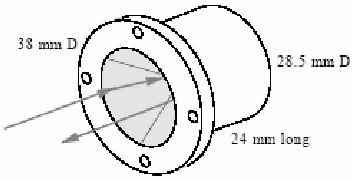
Beam Handling Components

- Beambender: A plane mirror:



  - Careful to make the bend 90º to avoid polarization leakage problems.
- Linear retroreflectors: Return light parallel to its incoming path:

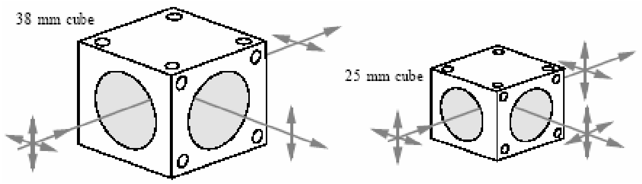




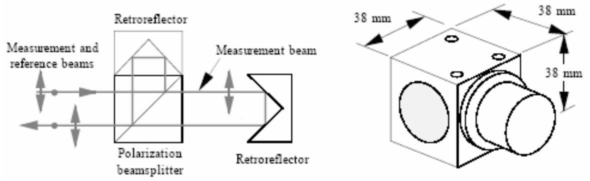
Source: Alexander Slocum, *Precision Machine Design*

Beam Handling Components (contd.)

- Beamsplitter: Separates orthogonally polarized beams into two components:

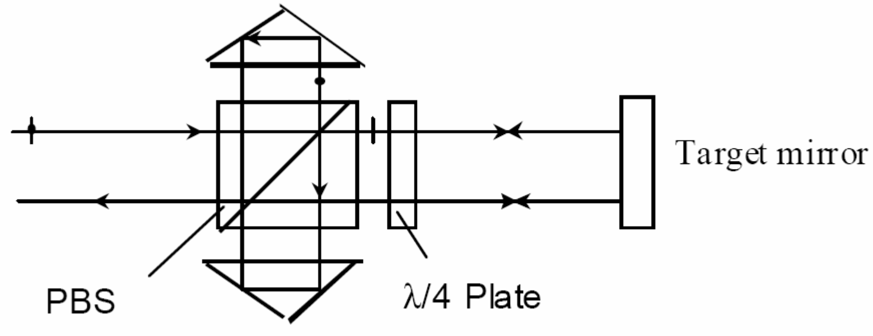


- Linear displacement interferometer: Combines polarization beamsplitter and a retroreflector:



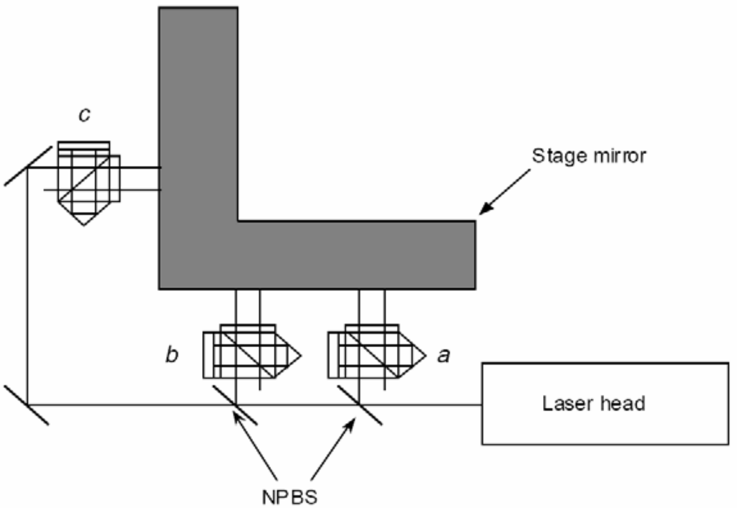
Source: Alexander Slocum, *Precision Machine Design*

Plane Mirror Interferometer



Source: Zygo

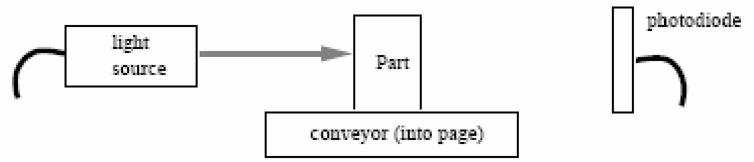
Wafer Stage Metrology



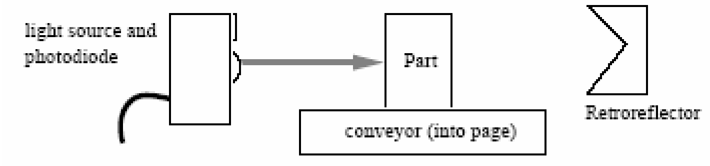
Source: Zygo

Photoelectric Transducers

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



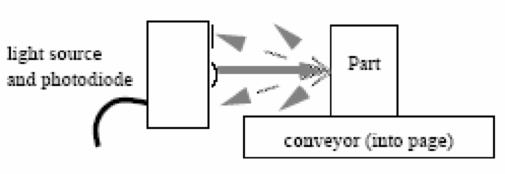
- Retroreflective mode operation of a photoelectric proximity sensor:



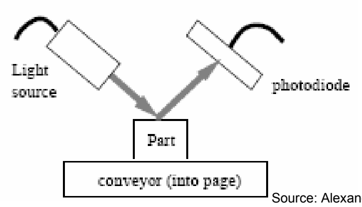
Source: Alexander Slocum, *Precision Machine Design*

Photoelectric Transducers (contd.)

- Diffuse reflection mode operation of a photoelectric proximity sensor



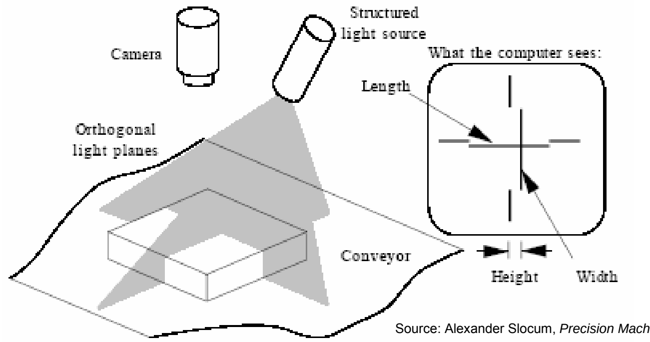
- Specular reflection mode operation of a photoelectric proximity sensor:



Source: Alexander Slocum, *Precision Machine Design*

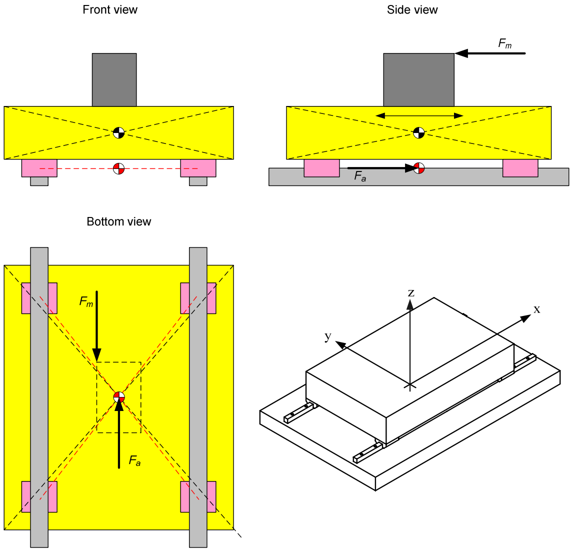
Vision Systems

- 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):

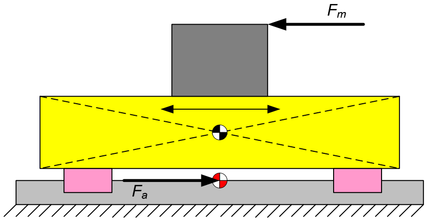


Source: Alexander Slocum, *Precision Machine Design*

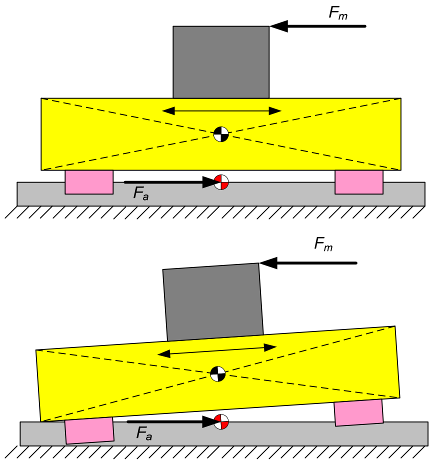
Sensor Positioning



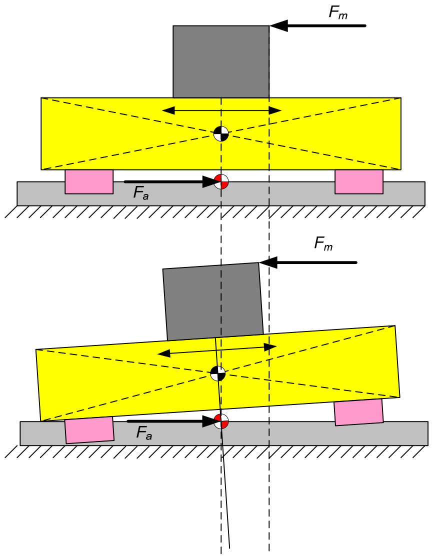
Vertical Sensor Position



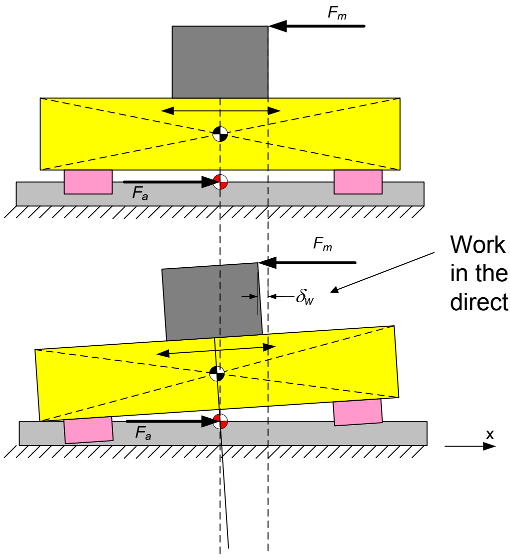
Vertical Sensor Position (contd.)



Vertical Sensor Position (contd.)

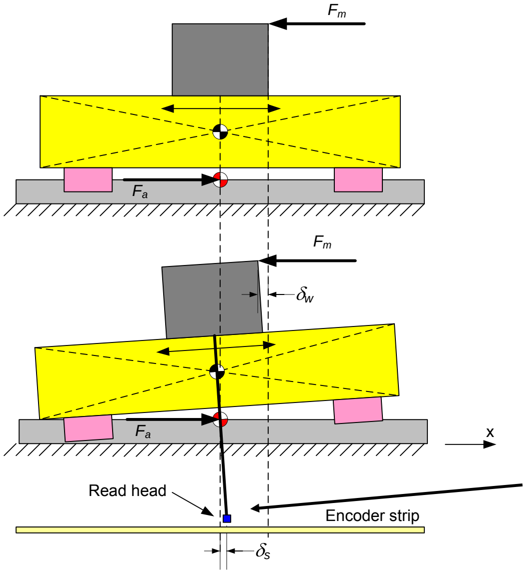


Vertical Sensor Position (contd.)



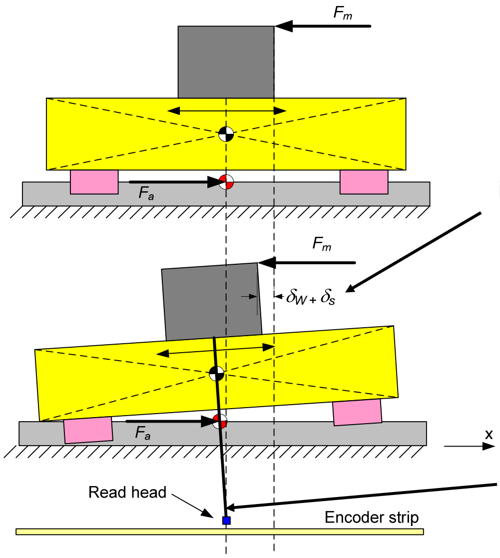
Work piece is pushed in the negative x-direction

Vertical Sensor Position (contd.)



Sensor below the center of stiffness is pushed in the positive x-direction

Vertical Sensor Position (contd.)



Error of work piece is now the sum of δ_w and δ_s

Control system regains target position by moving axis by $-\delta_s$

Conclusion

- The position of the sensor is critically important to the accuracy of a design
- As a rule of thumb, the sensor should be positioned as close as possible to the center of stiffness, but NEVER below