Precision Machine Design

Topic 8

Sensor systems

Purpose:

Machine designers must be aware of the types of sensor systems at their disposal. This lecture discusses selection of sensors, and how they are used which can have a large impact on system performance.

Outline:

- **Sensors and Transducers**
- **Sensor performance characteristics**
- **Common analog output sensors**
- **Common optical sensors**

"Experience is the name everyone gives to their mistakes"

Oscar Wilde

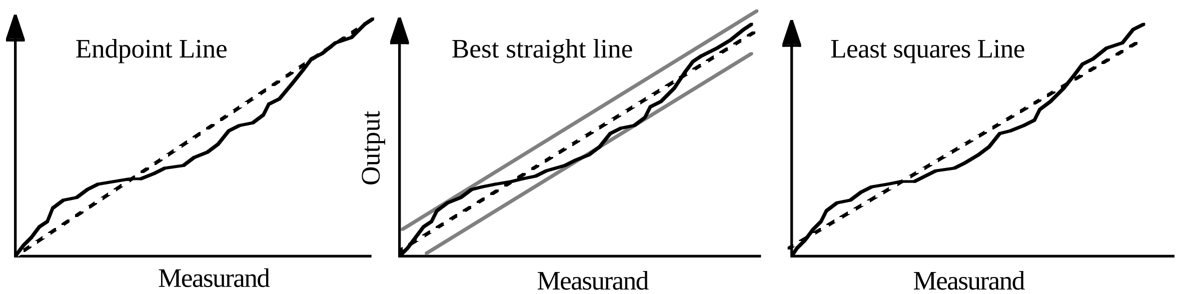
Sensors and Transducers

- **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.**
    - ***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.**
    - ***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.**

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.**

- ***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 verses input graph:**
        - **End point line.**
        - **Best straight line.**
        - **Least squares line.**



- **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.**

- ***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:**

Decibels (db)	Error
-0.0000087	1 ppm
-0.000087	10 ppm
-0.000869	100 ppm
-0.008690	1000 ppm
-0.087	1%
-0.915	10%
-3.0	30%

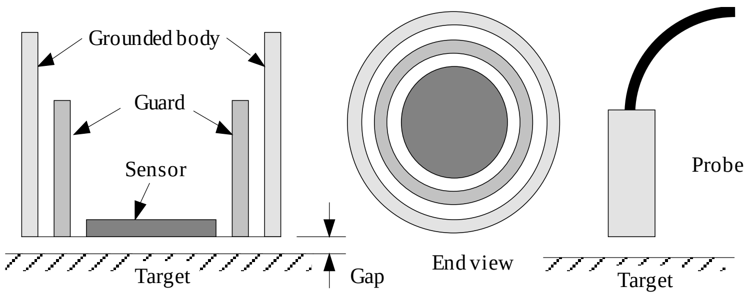
- **The phase angle portion of the dynamic response:**
  - **Affects whether a sensor can be effectively used in a control system for a machine.**
- **If there is too much lag:**
  - **It may not be possible for the mechanism to correct for errors sensed .**
  - **The error may have already irreversibly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

Common analog output sensors

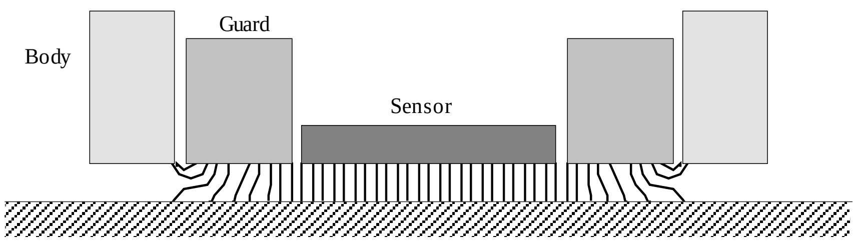
- **Capacitance sensors**
- **Hall effect sensors**
- **Inductive digital on/off proximity sensors**
- **Inductive distance measuring sensors**
- **Inductosyns™**
- **Linear & rotary variable differential transformers**
- **Magnetic scales**
- **Magnetostrictive sensors**
- **Potentiometers**
- **Velocity sensors**

Capacitance sensors

- **General construction**

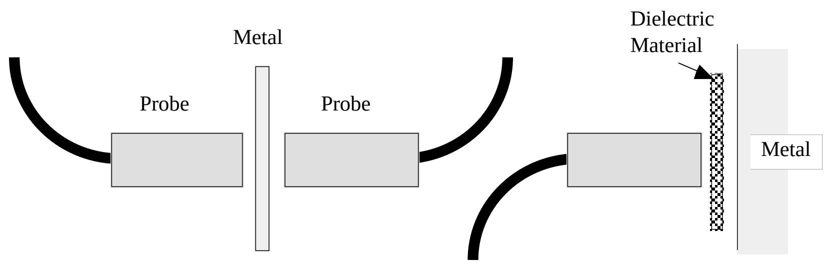


- **Field properties**

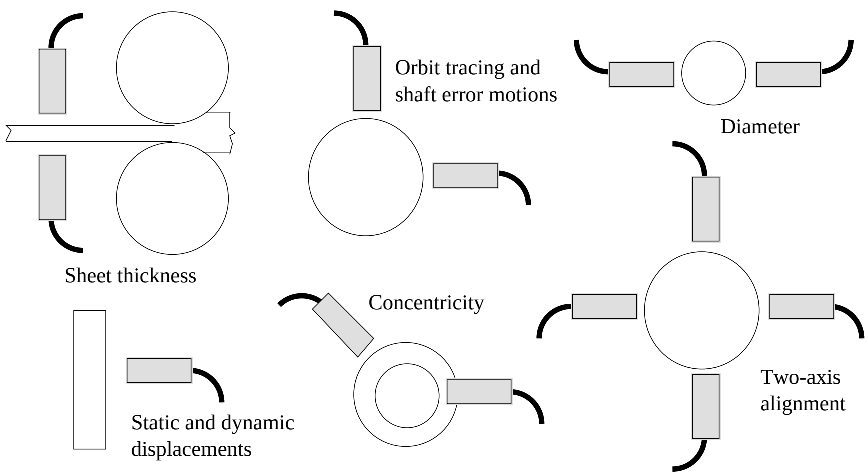


- **Generally regarded as the most accurate type of analog limited range of motion sensor.**

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

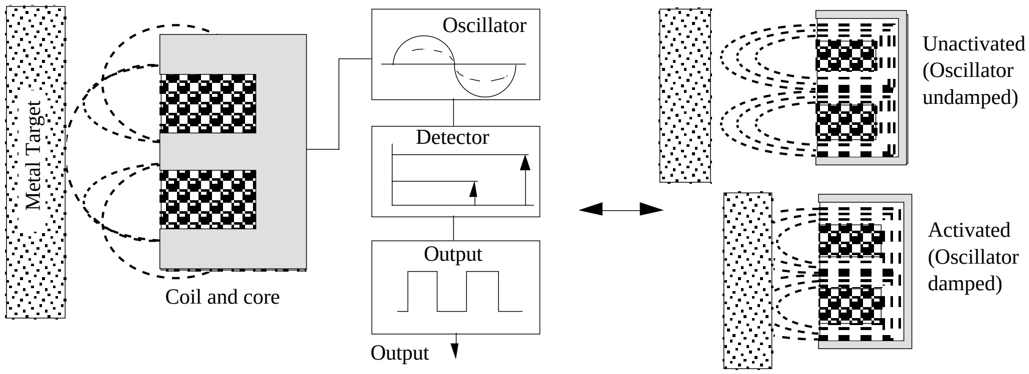


  - **Metrology equipment (e.g. spindle error analyzers):**



Inductive digital on/off proximity sensors

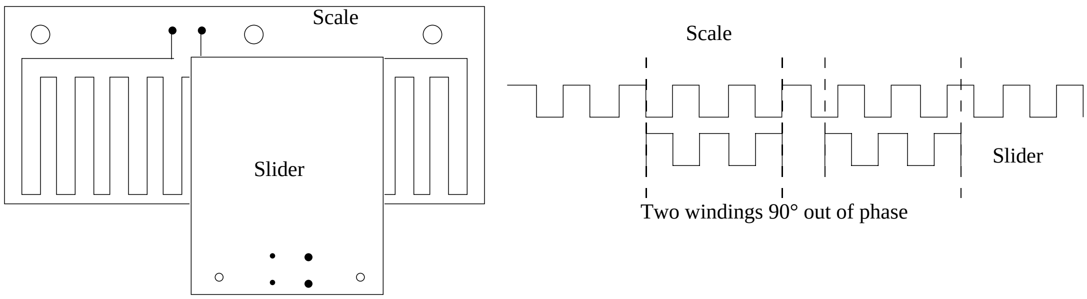
- **General operating principle** (Courtesy of Turck Inc.)**:**



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

Inductosyns™

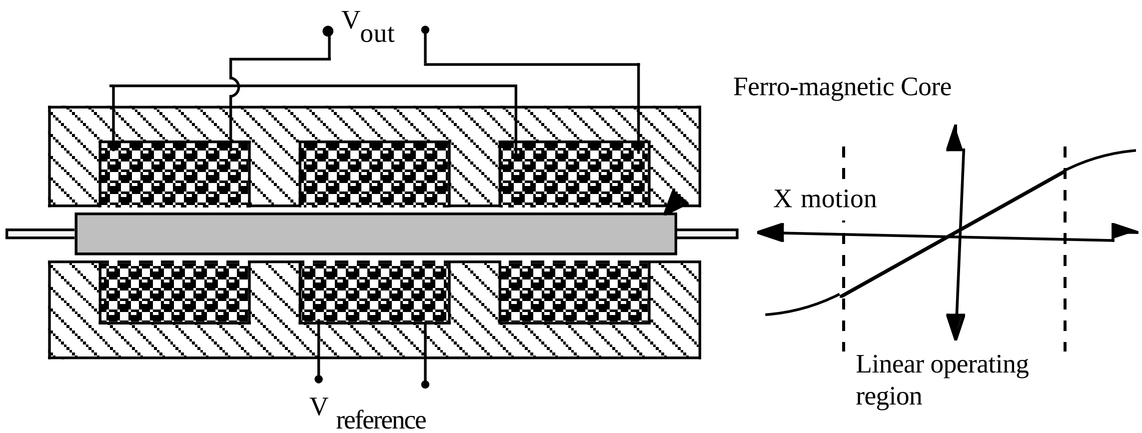
- **General operating principle:**



- **Rotary Inductosyns™ operate on a similar principle.**
- **Inductosyns™ were used on machine tools before robust encoders and magnetic scales were developed.**
- **Typical applications:**
    - **Rotary tables.**
    - **linear motion machine tool axes.**

Linear and rotary variable differential transformers

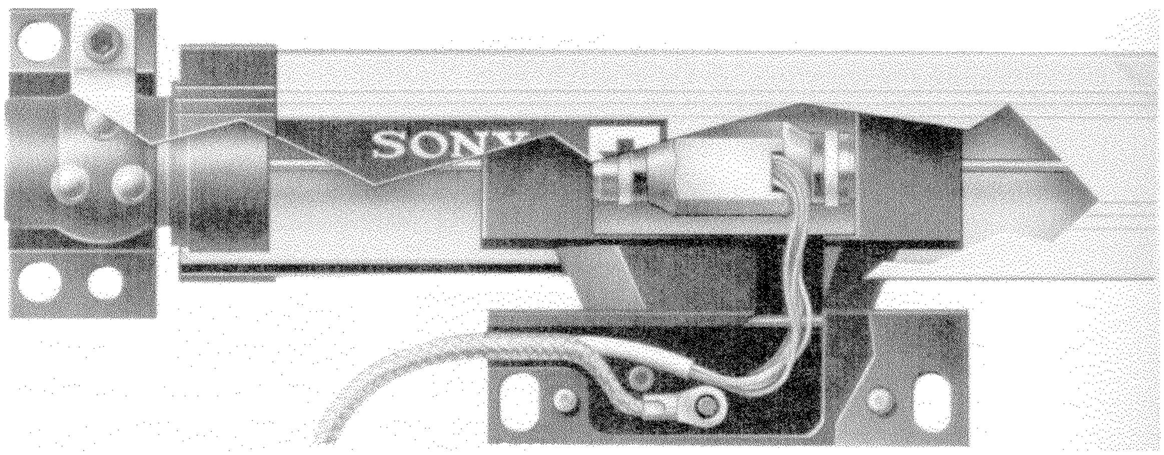
- **General operating principle** (Courtesy of Lucas Schaevitz)**:**



- **Typical applications:**
  - **Metrology equipment.**
  - **Small range of motion servo controlled devices.**

Magnetic scales

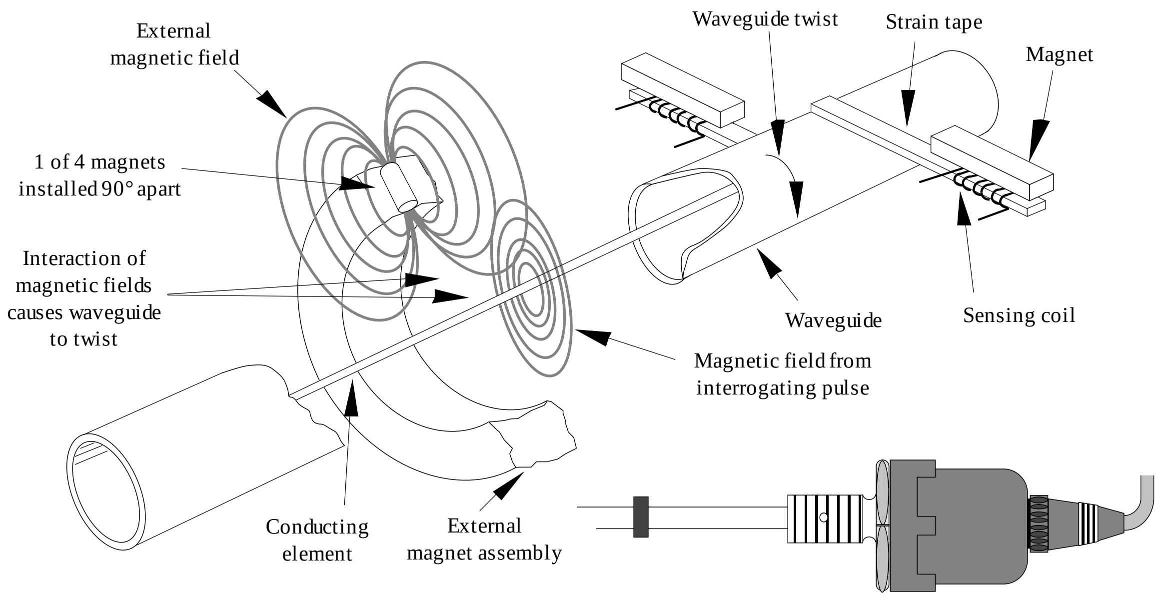
- **Operates on same principle that allows a disk drive to locate stored information.**
- **More robust then linear optical encoders.**
- **Magnetically encoded linear scale and sliding read head** (Courtesy of Sony Magnescale Inc.):



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

Magnetostrictive sensors

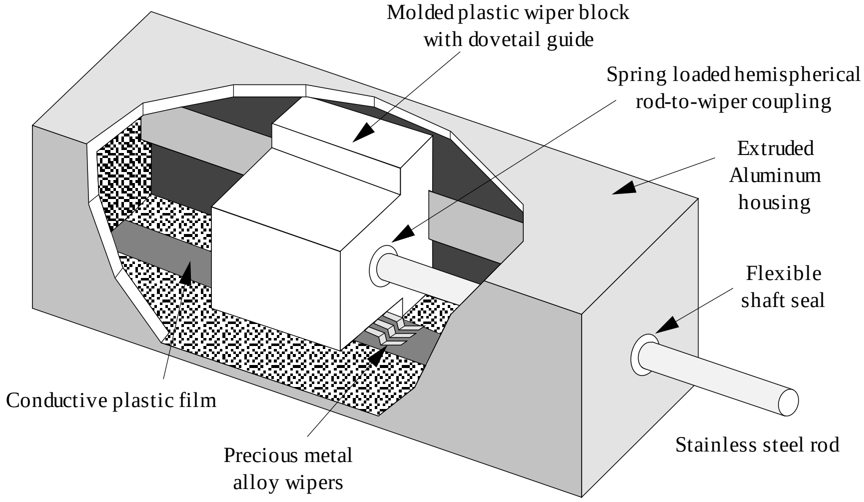
- **General operating principle for position sensing** (Courtesy of MTS Systems Corp.)**:**



- **Typical applications:**
  - **Moderate accuracy linear position sensing.**
  - **Position sensing of hydraulic pistons (sensor can be placed inside the cylinder).**

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.**

Velocity sensors

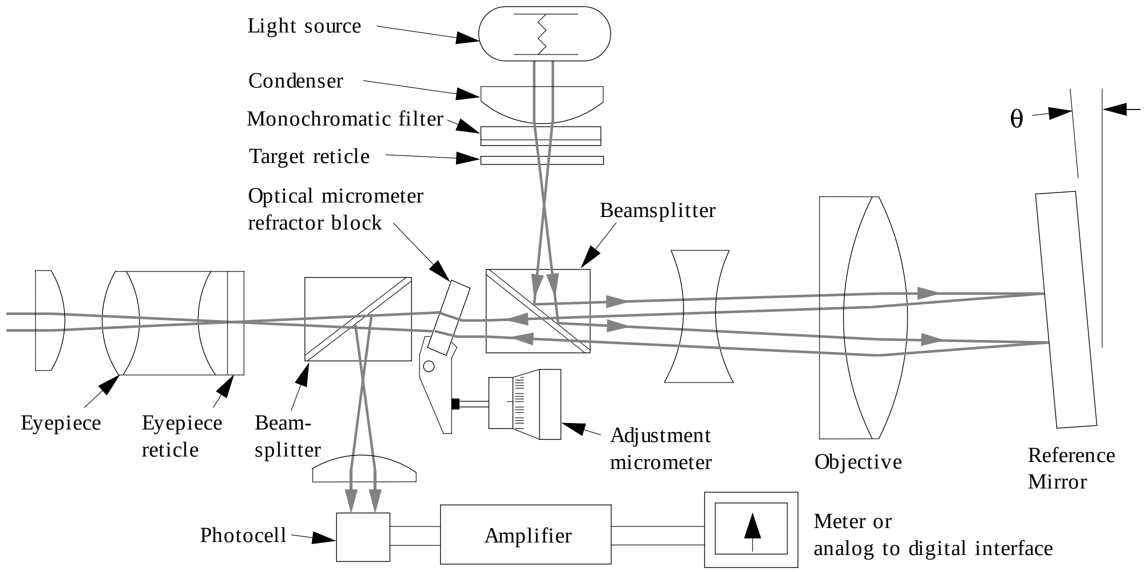
- **Linear velocity sensors tend to act like antennas, so they pick up EMI easily; thus their use should be avoided.**
- **Rotary velocity sensors (tachometers) are essentially driven DC motors.**
- **Typical applications:**
  - **Speed control.**
  - **Analog velocity feedback.**

Common optical sensors

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

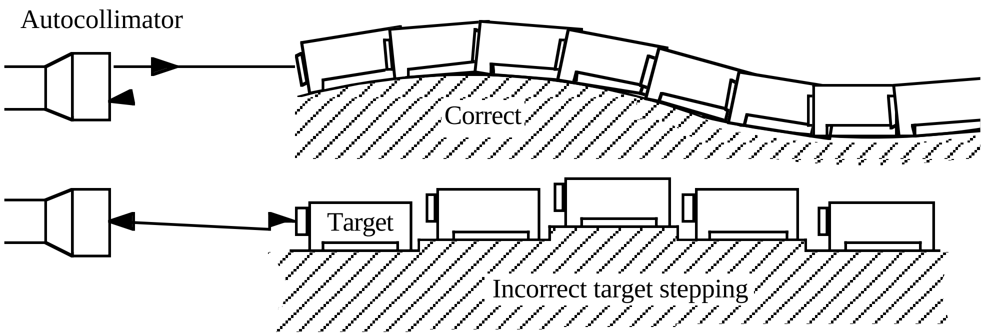
Autocollimators

- **Used to measure the change in angle of a target mirror.**
- **General construction** (Courtesy of Rank Taylor Hobson)**:**

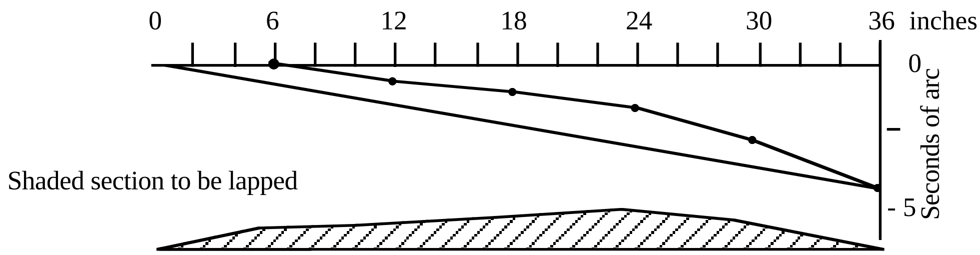


- **The measured angle is independant of the distance of the target.**

- **Typical applications:**
  - **Small angle servo systems.**
  - **Straightness measurement** (after Moore)**:**



Position (inches)	Reading seconds of arc	Accumulated seconds of arc	Correction seconds of arc	Actual error seconds of arc
6	0.0	0.0	+0.7	+0.7
12	-0.4	-0.4	+1.4	+1.0
18	-0.2	-0.6	+2.1	+1.5
24	-0.8	-1.4	+2.8	+1.4
30	-1.5	-2.9	+3.5	+0.6
36	-1.3	-4.2	+4.2	0.0

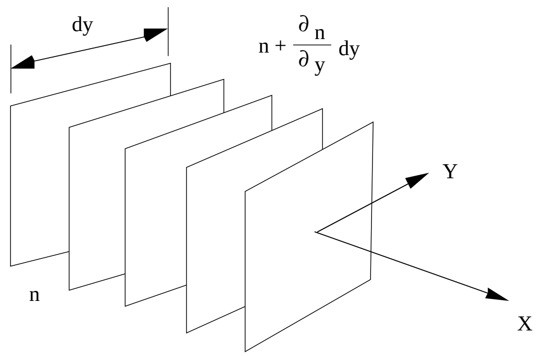


As with many optical systems, changes in the index of refraction affect sensor output

- **Edlen's equation:**

$$(n-1) \times 10^7 = (n_{nominal} - 1) \times 10^7 \times \frac{\text{Pressure}}{760 \text{ mm}} \times \frac{293°K}{T(°K)}$$

- **Effect of an index of refraction gradient (e.g., caused by a temperature gradient) on the propagation of a plane of light:**



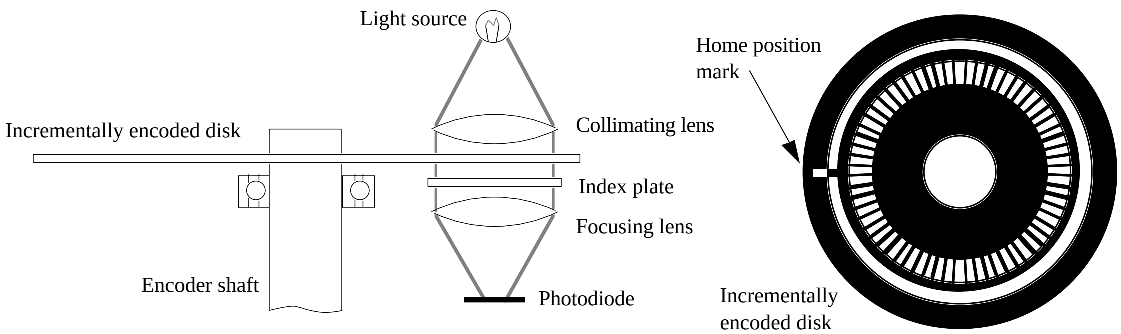
- **For small gradients dT/dy in air**

$$\frac{d\theta}{dx} \approx \frac{K}{nT^2}\left(\frac{dT}{dy}\right)$$

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.**

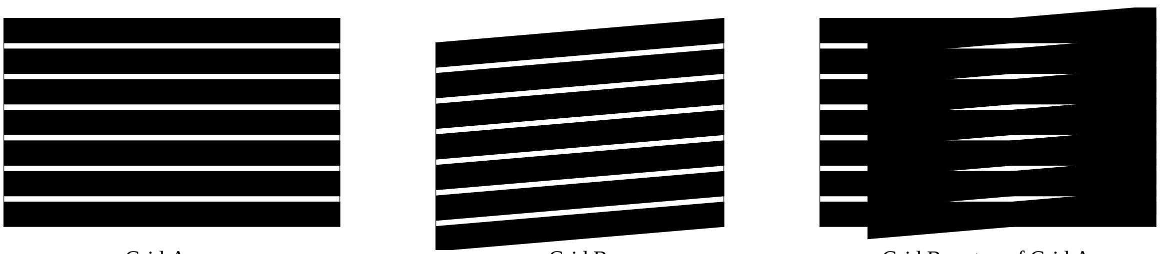
Incremental position encoders



- **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 90º±Nº, which cause velocity calculation errors in control loops.**

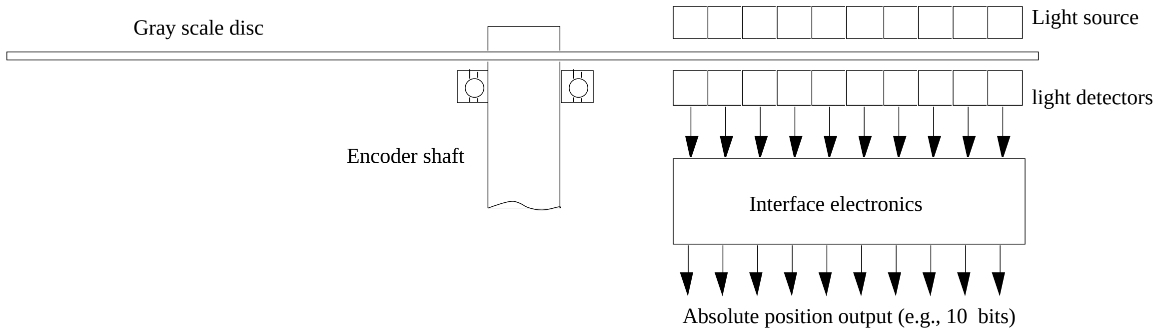
Interpolation encoders

- **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.**
- **Example, Moire fringes:**



Grid A Grid B Grid B on top of Grid A

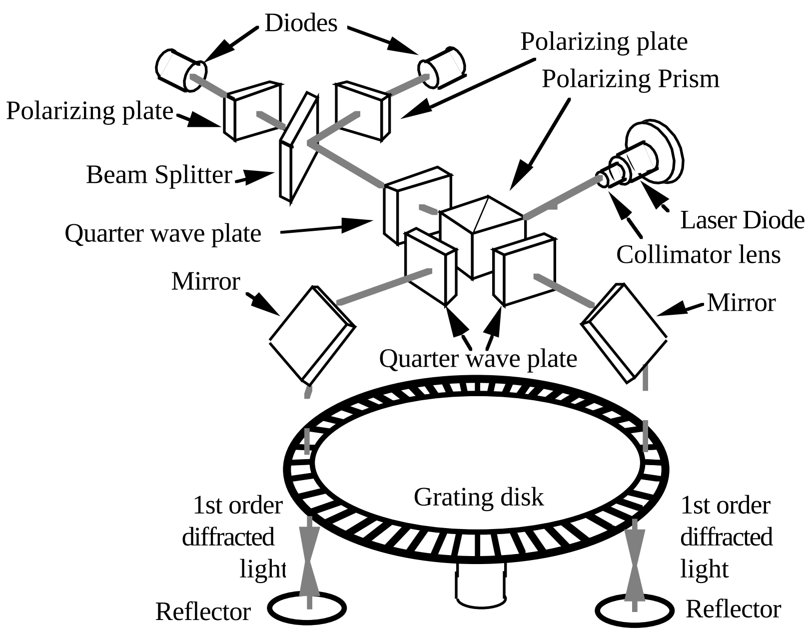
Absolute position encoders



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

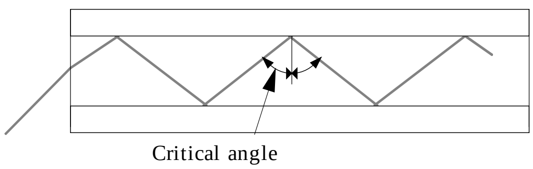
Diffraction encoders

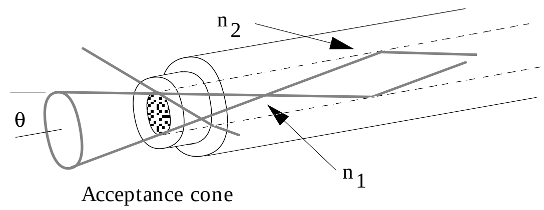
- **With conventional encoders, slit width and hence resolution is limited by diffraction.**
- **Diffraction encoders use diffracted light to create interference patterns.**
    - **These are used to generate very high resolution sine and cosine waveforms for interpolation.**
    - **Sine and cosine waveforms are assumed to be of equal amplitude.**
        - **This is a spurce of error that limits accuracy.**
- **Typical construction** (Courtesy of Canon USA Inc.)**:**



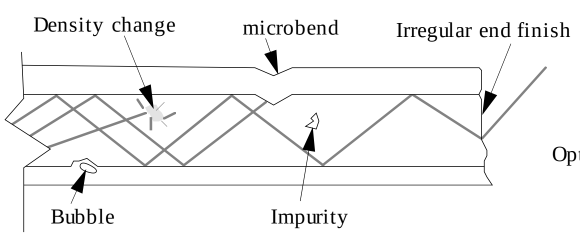
Fiber optic sensors

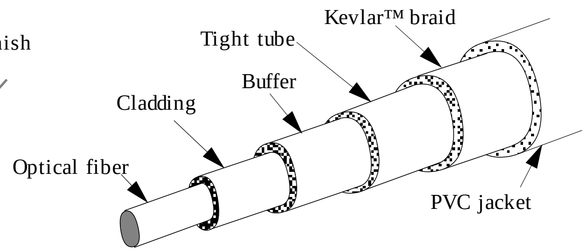
- **Condition for low loss propagation of light through a fiber** (Courtesy of 3M)**:**



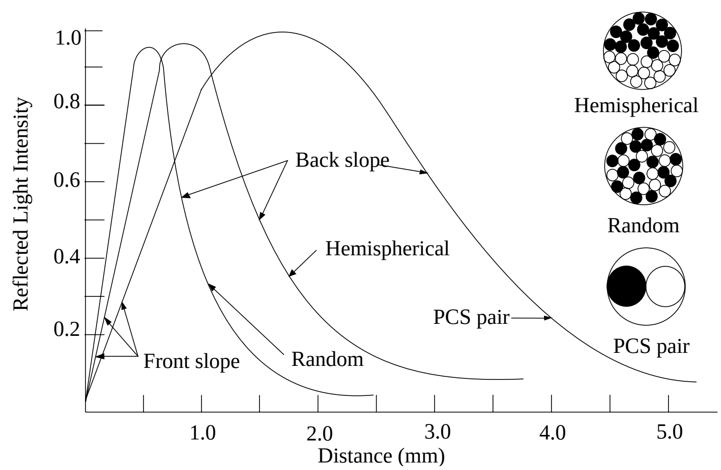


- **Construction of a fiber optic cable and typical defects** (Courtesy of 3M)**:**



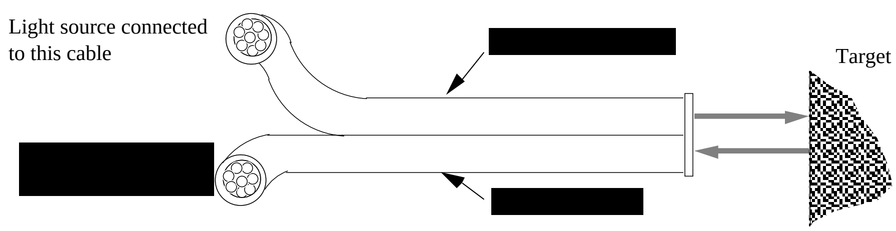


- **Generalized performance characteristics for three types of reflective fiber optic probes** (Courtesy of 3M)**:**



(Courtesy of 3M)

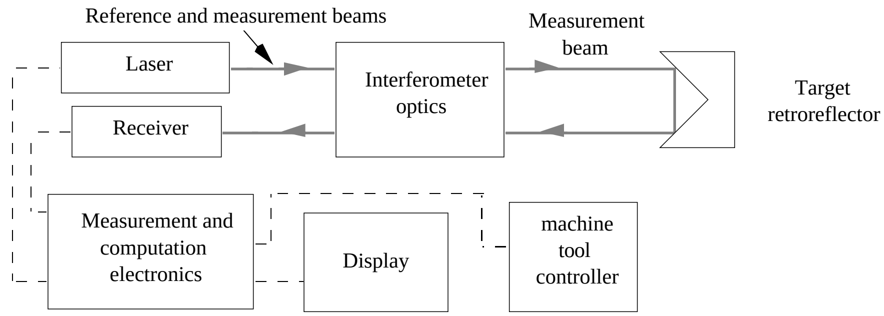
- **Bifurcate probe used in a reflective scanning mode** (Courtesy of 3M)**:**



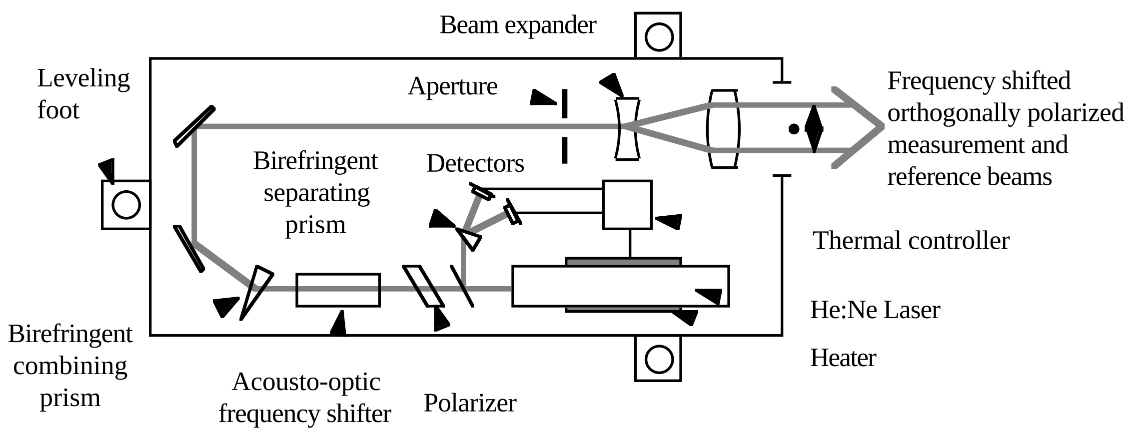
- **Typical applications of fiber optics in precision machines:**
  - **To carry light to or from a sensor (e.g. interferometer).**
  - **To carry light to and from a surface for measuring the position of the surface.**

Optical Heterodyne Interferometers

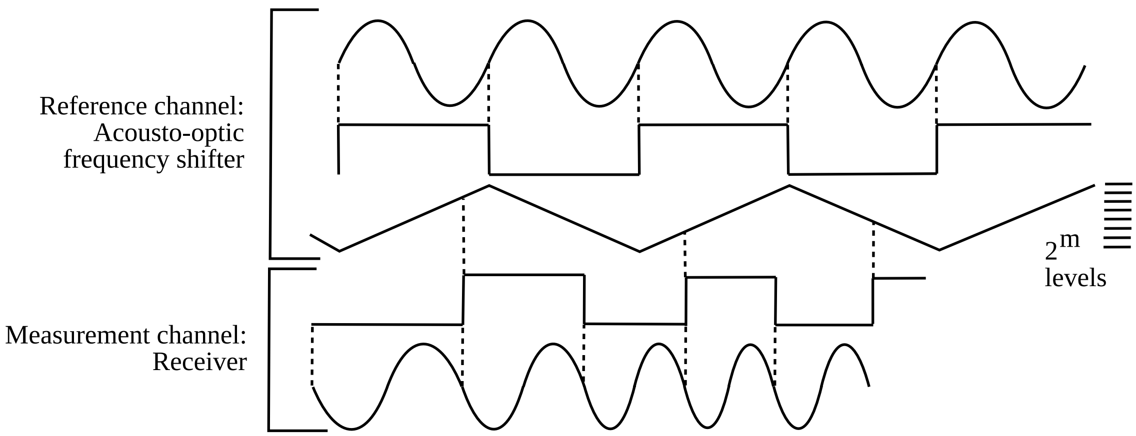
- **Michelson interferometers count fringes which limits the resolution to about l/8.**
- **Heterodyne techniques can be used to achieve two orders of magnitude greater resolution:**



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

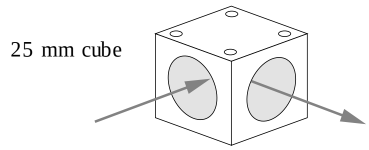


- **One of many processes for determining optical path change using phase measurement** (Courtesy of Zygo Corp.)**:**



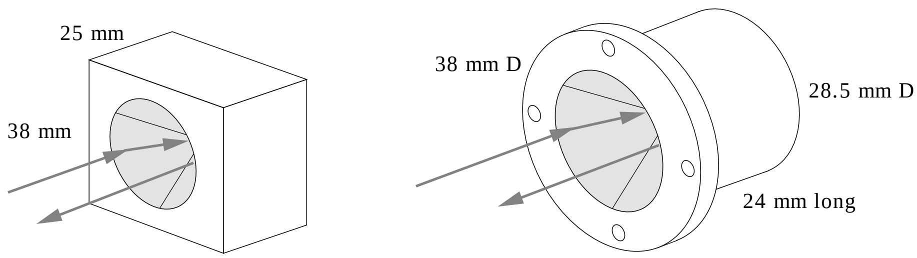
Beam handling components

- **Beambender: A plane mittor:**

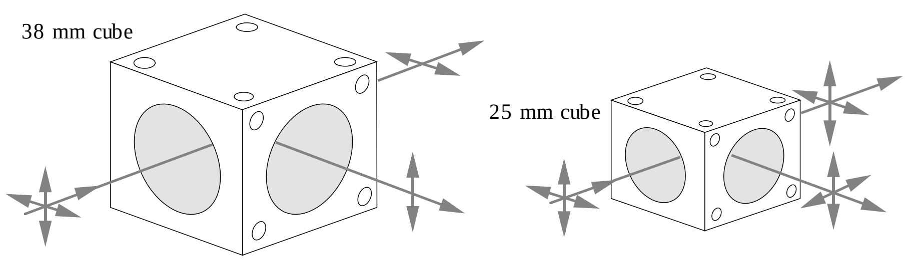


  - **Careful to make the bend 90º to avoid polarization leakage problems**

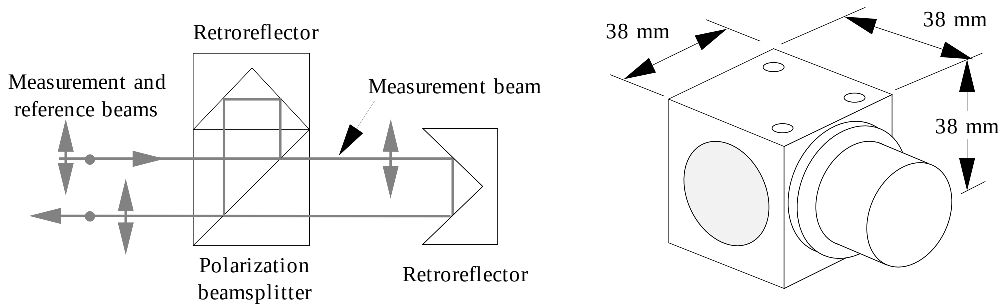
- **Linear retroreflectors: Return light parallel to its incoming path:**



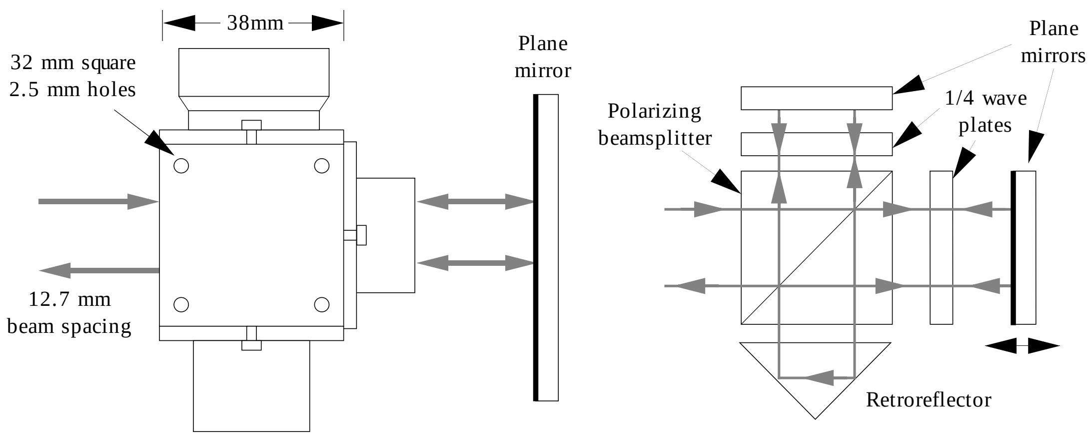
- **Beamsplitter: Separates orthogonally polarized beams into two components:**



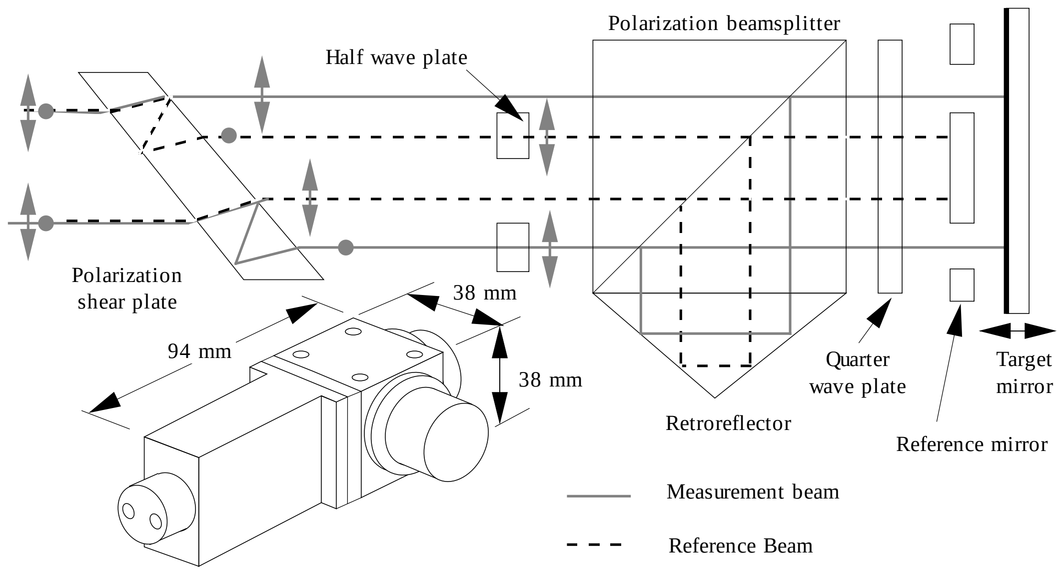
- **Linear displacement interferometer: Combines polarization beamsplitter and a retroreflector:**



- **Plane mirror interferometer** (Courtesy of Zygo Corp.)**:**

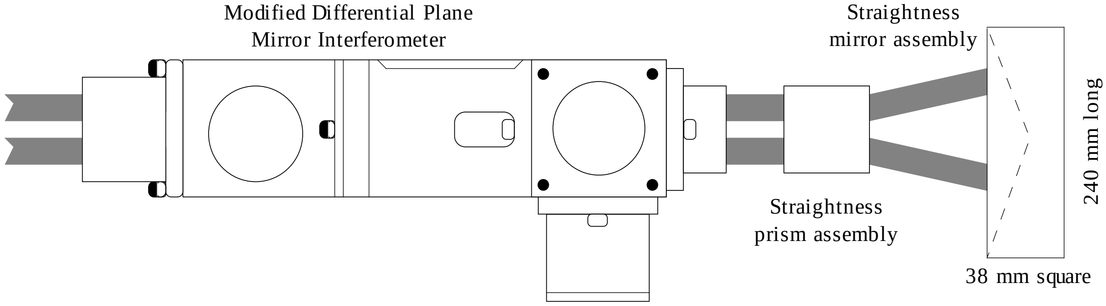


- **Differential plane mirror interferometer for linear or angular motion measurements** (Courtesy of Zygo Corp.)**:**



- **For linear measurements, the reference mirror lets beams pass through diagonally opposite holes.**
- **For angular measurements:**
  - **The reference mirror lets beams pass through holes aligned on an axis parallel to the axis of rotation.**

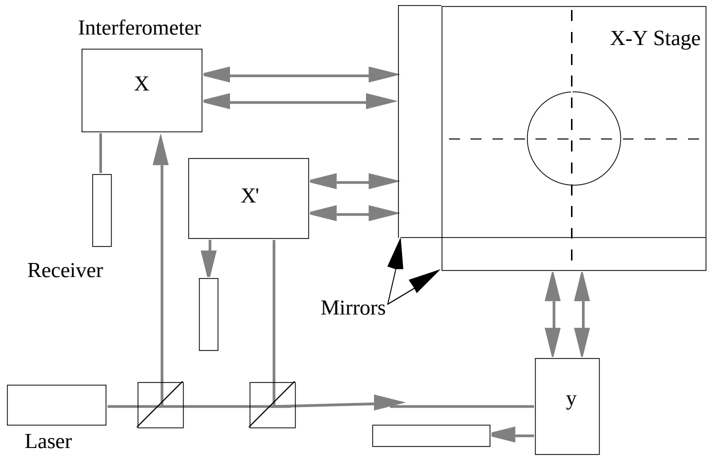
- **Straightness interferometer and reflector** (Courtesy of Zygo Corp.)**:**



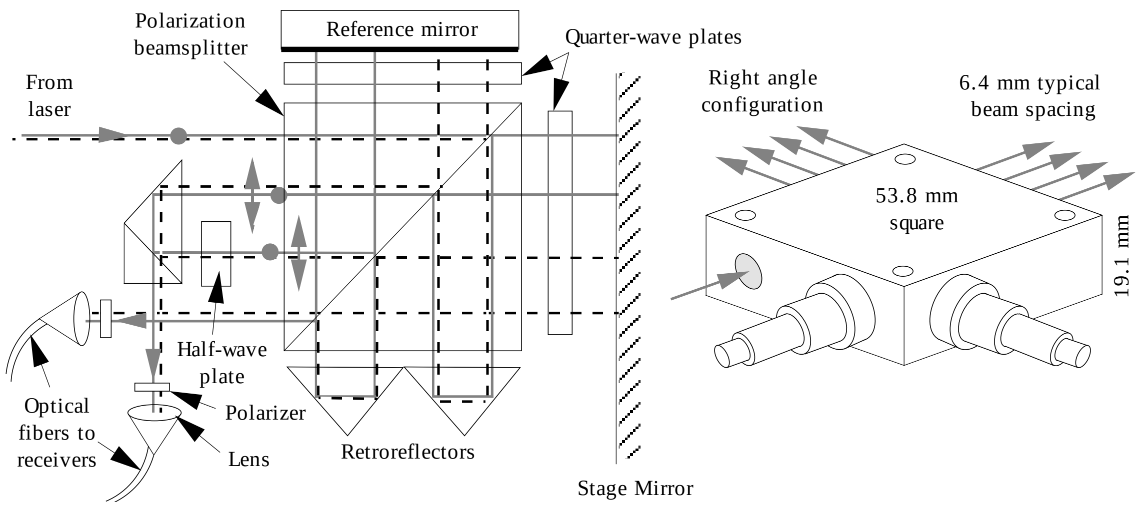
  - **Straightness motion of the prism or the mirror causes the pathlength to change.**
  - **Errors in a or flatness of mirror cause straightness measurement accuracy to be limited to about 1/4 µm.**

- **Greatest straightness accuracy is obtained by:**
  - **Achieved by using a plane mirror interferometer to measure motions with respect to a precision straightedge.**

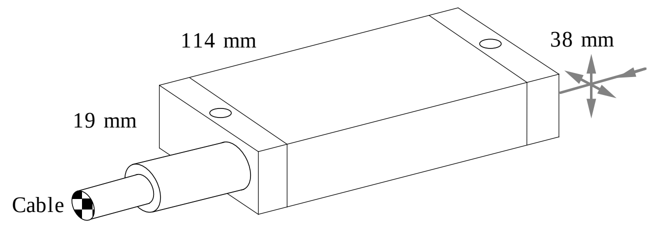
- **Typical wafer stage metrology using a laser measurement system** (Courtesy of Zygo Corp.)**:**



- **Linear/angular displacement interferometer** (Courtesy of Zygo Corp.)**:**

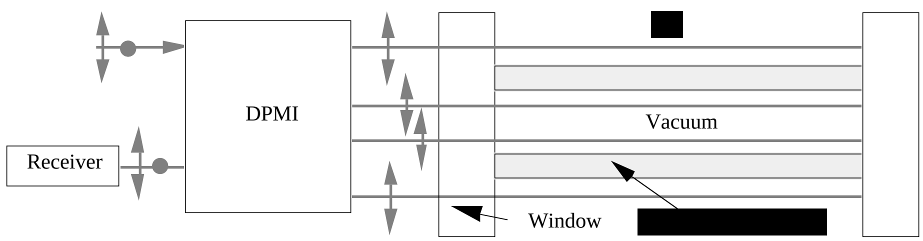


- **Measurement receiver:**



  - **Some systems replace the reciever with a lens-pickup and fiber optic cable which plugs into the interferometer's electronics board.**

- **Refractometer for measuring changes in the refractive index of air** (Courtesy of Zygo Corp.)**:**



Sources of error

- **Refractive index errors'magnitudes can be estimated from a modified form of Edlen's equation:**

$$n-1 = \frac{2.879294 \times 10^{-9} (1 + 0.54 \times 10^{-6} (C - 300))P}{1 + 0.003671 \times T} - 0.42063 \times 10^{-9} \times F$$

C is the CO_2 content in ppm
F is the water vapor pressure in Pa
P is the air pressure in Pa
T is the air temperature in ^oC

$$\frac{\partial n}{\partial C} = \frac{1.55482 \times 10^{-15} \times P}{1 + 0.003671 \times T}\ ppm^{-1} \approx 1.45 \times 10^{-10}\ ppm^{-1}$$

$$\frac{\partial n}{\partial F} = - 4.2063 \times 10^{-10} \times Pa^{-1}$$

$$\frac{\partial n}{\partial P} = \frac{2.87929 \times 10^{-10} (1 + 5.4 \times 10^{-7} (C\text{-}300))}{1 + 0.003671 \times T}\ Pa^{-1} \approx 2.67 \times 10^{-9} \times Pa^{-1}$$

$$\frac{\partial n}{\partial T} = \frac{- 1.05699 \times 10^{-11} (1 + 5.4 \times 10^{-7})\ (C\text{-}300))\ P}{(1 + 0.003671 \times T)^2}\ K^{-1} \approx -9.20 \times 10^{-7} \times K^{-1}$$

- **Thermal effects clearly dominate.**

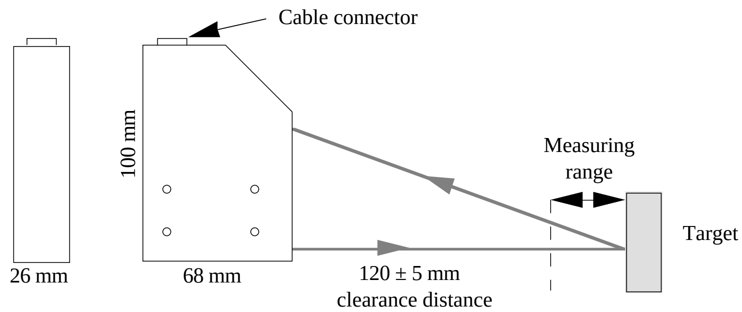
Other sources of error

- **Air turbulence:**

Beam path condition	rms optical path fluctuation (Å) over 175 mm path
Enclosed	4
Unenclosed	15
0.5 m/s	24
1.0 m/s	45
0.5 m/s nozzle	24
1.0 m/s nozzle	45

- **Light wavelength errors.**
- **Electrical noise errors.**
- **Alignment errors:**
  - **Cosine errors.**
- **Optical component errors:**
  - **Shape of the optics.**
  - **Nonuniformity of refractive index.**
  - **Nonuniformity of coatings on the optics.**

Laser triangulation sensors

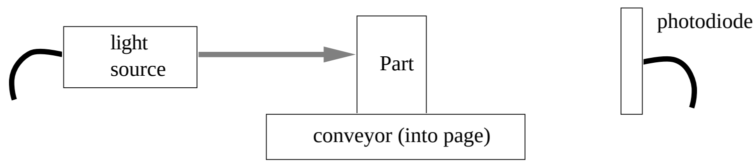


(Courtesy of Candid Logic Inc.)

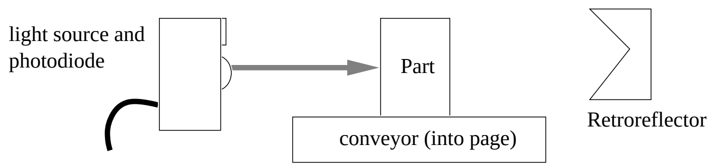
- **Typically used as non-contact displacement sesnors.**
- **Very useful for gauging applications**

Photoelectric transducers

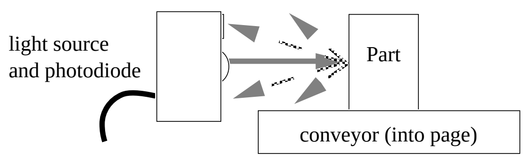
- **Opposed mode (interrupted beam) operation of a photoelectric proximity sensor:**



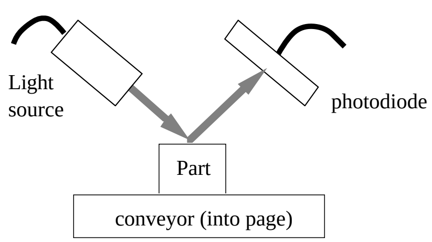
- **Retroreflective mode operation of a photoelectric proximity sensor:**



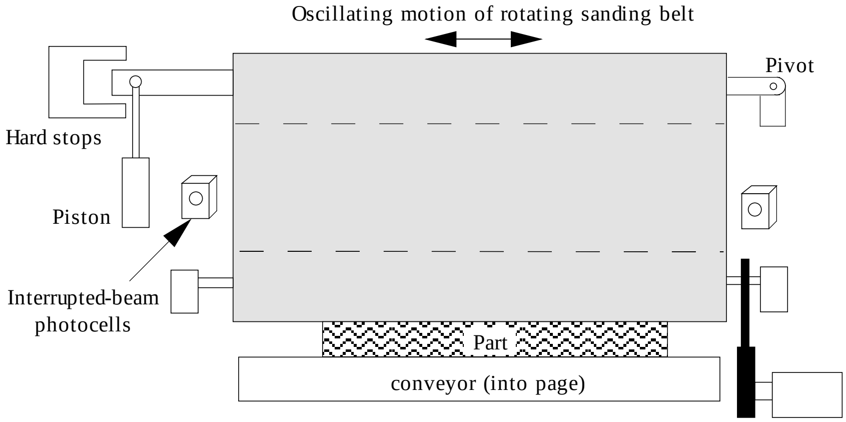
- **Diffuse reflection mode operation of a photoelectric proximity sensor.**



- **Specular reflection mode operation of a photoelectric proximity sensor:**

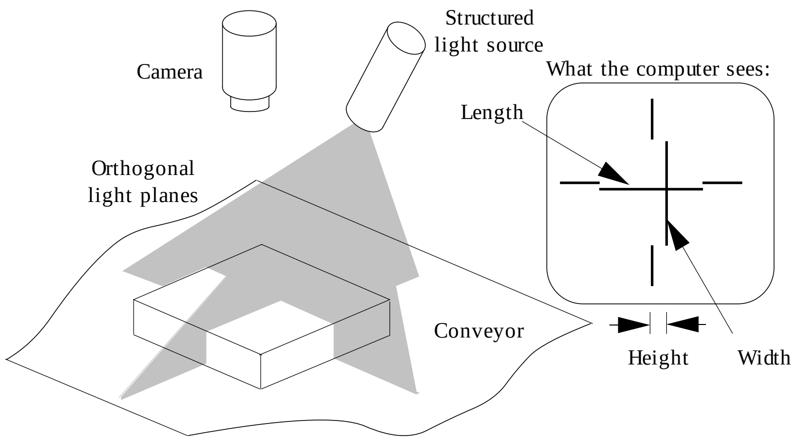


- **Photoelectric proximity sensor used to control oscillating motion of a sanding machine's belt:**



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.**

- **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**