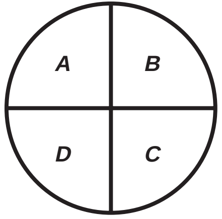
Non-contact Position Sensing Using Optical Detectors

Quadrant Detector



$$X\ Position = \frac{(A+D) - (B+C)}{A+B+C+D}$$

$$Y\ Position = \frac{(A+B) - (D+C)}{A+B+C+D}$$

Quadrant detector electrical connections and formulas.

Conversion Formulas

The position of a light spot with respect to center on a quadrant detector is found using:

$$X=((A+D) - (B+C)) / (A+B+C+D)$$
$$Y=((A+B) - (C+D)) / (A+B+C+D)$$

where A,B,C and D are the photocurrent produced in each segment. The difference signal is divided by the sum in order to cancel out the effects of light level variation.

For continuous position sensors the formulae are also simple. For a one-dimensional device.

$$2x/L=(X_2-X_1) / (X_1+X_2)$$

Where X_2 and X_1 are the photocurrent signals from each contact, and x is the position along the axis.

Similarly, position is calculated for dual-axis tetra-lateral or duo-lateral devices using:

$$2x/L=(X_2-X_1) / (X_1+X_2)$$
$$2y/L=(Y_2-Y_1) / (Y_1+Y_2)$$

The formulae are just slightly more complex for pin-cushion types:

$$2x/L=((X_2+Y_1) - (X_1+Y_2)) / (X_1+X_2+Y_1+Y_2)$$
$$2y/L=((X_2+Y_2) - (X_1+Y_1)) / (X_1+X_2+Y_1+Y_2)$$

High-performance electronic circuits that perform these simple arithmetic functions are incorporated into UDT Instruments position sensing instruments such as the Models 531 and 431, and into the 301 Series Differential Amplifiers.

To understand optical position sensing instruments, it's important to understand the sensors they make use of. These form the heart of the systems, and fall into two basic categories: segmented and continuous.

Segmented Position Sensing Detectors

Also known as quadrant and bi-cell detectors, these devices have two or four distinct photosensitive elements separated by a minuscule gap.

A light spot illuminating just one element only produces photocurrent in that element. When the spot is translated across the surface of the detector, the energy becomes distributed between adjacent elements. The ratio between the photocurrent outputs from these elements determines the relative position of the spot on the surface.

It's important to note that the detector only provides position information over a linear distance of the spot diameter. Elsewhere, it is known to be in a specific segment, but not exactly where. Because of this, when working with lasers, defocusing may be required in order to obtain maximum range.

With a segmented device, another spatial consideration is key: The response to movement of a circular spot is non-linear. This is because the ratio of the spot's movement to the percentage of its area that shifts between adjacent segments is nonlinear.

For these reasons, segmented detectors are best used as nulling and centering devices. And for such applications, their performance is unparalleled. In fact, a repeatability of 0.1µm has been routinely demonstrated. This high resolution stems from the almost perfect response uniformity between elements. Also, with light-level sensitivities approaching one picowatt, segmented devices will work with far dimmer sources than will continuous position sensing detectors.

Continuous Position Sensing Detectors

When position sensing applications require measurement over a wide spatial range, continuous detectors are the right choice.

The primary difference between segmented detectors and continuous ones is that the latter are single photodiode. There is no gap or dead region between cells.

Continuous position sensing detectors derive position by dividing photo-generated electrons within their substrate, not by profiling intensity distribution on the surface as segmented detectors do. Therefore, a 2-axis continuous sensor acts as a pair of light-controlled variable resistors that measure the X and Y position of an incident light spot.

Compared to segmented detectors, the primary advantage of continuous position sensors is their wide dynamic range: They measure the position of a light spot right out to their edge. It's also important to note that these sensors determine the centroid of a light spot. This gives them the advantage of being indifferent to a spot's shape or intensity distribution.

For nulling or centering applications, the spatial resolution of a continuous device is inferior to that of a comparable segmented device. This stems from the lower signal-to-noise ratio of continuous devices. So continuous position sensors work best for measuring a light spot's movement over a wide range.

Continuous position sensors are available in one- and two-dimensional configurations, and come in four types—duo-lateral, tetra-lateral, pin-cushion and transparent duo-lateral.

The duo-lateral type has electrodes on both its front and rear surfaces. From the equivalent circuit it can be seen that each position signal is divided into just two parts...but by two separate resistive layers. This approach produces minimal position sensing error and very high resolution.

Tetra-lateral types have four electrodes on the front surface of the photodiode. As such, the total induced photocurrent is divided into 4 parts by the same resistive layer. Compared with the duo-lateral type, tetra-lateral devices are more non-linear for positions further from their mechanical centers. However, the tetra-lateral devices produce less dark current and have a faster response time. And they are somewhat easier to operate since minimal, or even zero, bias voltage is required.

Pin-cushion devices are basically an improved tetra-lateral, with reduced signal non-linearity at the edges. This is achieved by increasing the photodiode's surface sensitivity and modifying its electrodes. The pin-cushion device offers all the advantages of the tetra-lateral type. namely, low dark current, fast response, and minimal bias-voltage requirements.

Transparent duo-lateral detectors are essentially the same in principle as duo-lateral. However, they are constructed by depositing amorphous silicon on a transparent substrate. Thus, an incident beam can pass right through the detector after experiencing a small amount of attenuation and diffusion.

Calculating Position Resolution

Definition:

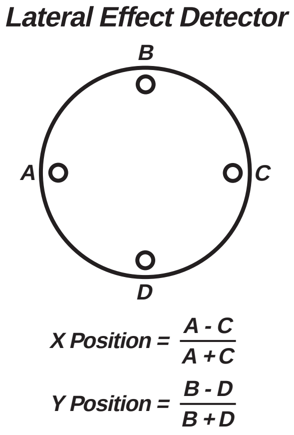
Resolution is defined as the minimum displacement that can be resolved by a position sensor in a given electro-optical system.

Consider a single-axis, lateral-effect position sensor which produces current x_1 and x_2. Position is given by:

$$P = \left(\frac{x_1 - x_2}{x_1 + x_2} \right) \frac{L}{2}$$

However, there is uncertainty in the values of x_1 and n_2. Therefore, the measured position is:

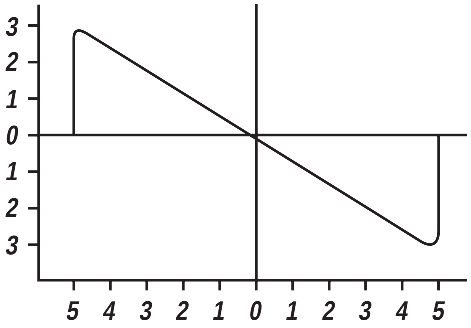
$$P_{meas} = \left[\frac{(x_1 \pm n_1) - (x_2 \pm n_2)}{(x_1 \pm n_1) + (x_2 \pm n_2)} \right] \frac{L}{2}$$



$$X\ Position = \frac{A - C}{A + C}$$

$$Y\ Position = \frac{B - D}{B + D}$$

Lateral-effect detector electrical connections and formulas.



Linear transfer function of lateral-effect diodes.

Maximum error occurs when both noise signals are negative and approximately equal in value. The maximum measured position is:

$$P_{meas(max)} = \left[\frac{x_1 - x_2}{x_1 + x_{2+2n}}\right]\frac{L}{2} \ldots\ldots ①$$

Since the signal-to-noise ratio is:

$$S/N = \frac{x_1 + x_2}{2n}$$

We can solve for n and substitute into Equation①, to obtain a maximum error value in terms of the signal-to-noise ratio which we can readily estimate and control. Thus:

$$P_{meas(max)} = \left[\frac{x_1 - x_2}{x_1 + x_2 - \left(\frac{x_1 + x_2}{S/N}\right)}\right]\frac{L}{2}$$

$$= \frac{S/N}{S/N - 1}\left(\frac{x_1 - x_2}{x_1 + x_2}\right)\frac{L}{2}$$

is the worst case erroneous measurement.

The Modulus of Error is:

$$\delta P = \left(\frac{1}{S/N + 1}\right)\frac{L}{2}$$

If S/N>>1 then:

$$\delta P = \frac{L}{2\,{}^{S}\!/\!_{N}}$$

For a typical 10 mm x 10 mm tetra-lateral type photodiode, one can expect a noise equivalent current of about 40 nA, and a maximum signal current of about 200 µA. As such, in spatial terms, the noise equals 1 micron.

Resolution of a position sensor should not be confused with accuracy or linearity. The resolution is independent of these properties which are intrinsic to the type of detector and not to the signal-to-noise ratio of the system.

It is interesting to note that this formula for resolution equally applies to a bi-cell when one considers L as the spot diameter.

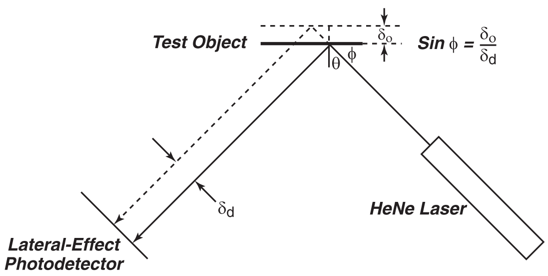
Sensing Displacements of Specular or Diffuse Surfaces

Up to this point we have discussed how to resolve the position of a light spot on the surface of a detector. Now let us define how this relates to resolving the position of a test object or light source.

Measuring Linear Displacement

For all cases $0° < \phi < 90°$:

$$\delta_o = \frac{\delta_d}{2\cos\phi}$$



Test object linear displacement measurement.

Measuring Rotation About A Fixed Point

In this case, we know that:

$$L = \frac{\delta_d}{\tan\delta_\phi}$$

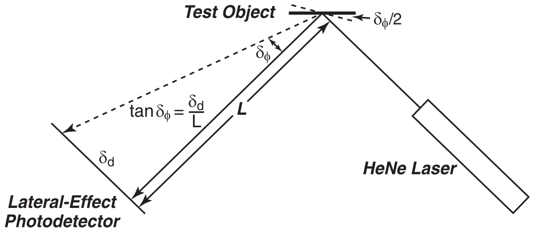
So the detector's position resolution is related to angular resolution in the object plane by:

$$L \leq \frac{\delta_{d(\min)}}{\tan\delta_{\phi(\min)}}$$

Similarly, the photodetector must have an active length of:

$$\delta_{d(\max)} \geq L\tan\delta_{\phi(\max)}$$

Error may occur if linear displacement and rotation occur at the same time, since the position sensor cannot distinguish between the object's linear and angular movements. However, the error may be corrected by employing a photodetector to measure the combined effect, and an autocollimator to measure rotation alone.

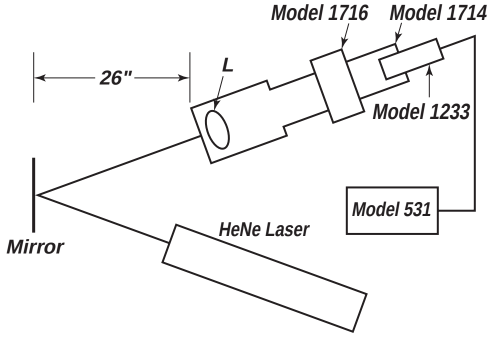


Test object rotation measurement.

Remote Angle Sensing

One of the primary uses of position sensing detector is for measuring angles, usually of mirrors but sometimes of relatively diffuse surfaces. UDT Instruments manufactures a number of electronic autocollimators that connect directly to the Models 531 and 431.

However, under special situations where the distance to the mirror is large, or where the mirror itself is small, the configuration shown here works well.



Remote angular sensing.

The 2 mW helium-neon laser is positioned approximately two feet from the mirror under test. The receiving lens and the working distance are chosen to provide the desired mirror angular coverage. In this example, a 2-inch diameter 135 mm focal length lens would cover a mirror tilt of 38 milliradians.

The Model 531 should be set to bias the detector to operate in the photoconductive mode when a relatively high power light source such as HeNe laser is used. Otherwise, the detector will saturate and become nonlinear.

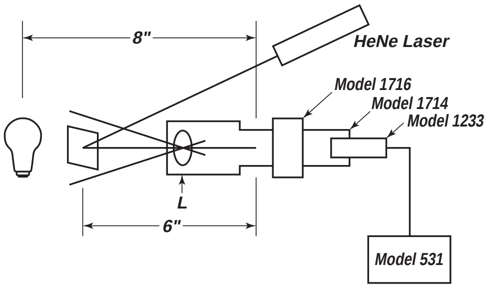
Varying the lens focal distance varies the angular sensitivity. A bare detector may also be used, however, it will limit the angular coverage.

Sensing the Position of Moving Objects

Here, two cases are considered, both using the same detector configuration. Real-world applications include sensing the position of machine tools and robot arms, or monitoring movement in bioengineering.

Case 1: The light source is a 20 mW helium-neon laser shining onto a white, diffuse, lambertian surface. Using a 28 mm focal length f/2.8 camera lens, the field of view of the lens system at 6 inches if 2.1 inches (given a detector with a 0.4 x 0.4 inch active area). A narrow-band 633 nm filter will reduce detector sensitivity to ambient light. A faster lens and shorter working distance will utilize the Model 531's accuracy to an even greater extent.

Case 2: Using a 1000 W tungsten lamp, working distances up to or greater than 200 feet are possible. For instance, for the Model 531 set on low gain, at 8 feet with an f/1.4 lens, the signal level is 8% of full scale. Using a higher gain on the Model 531 adds another factor of 1000 to the signal level. Therefore, on high gain the same performance can be achieved at 250 feet. Using reflectors and optics with the lamp further extends this range.



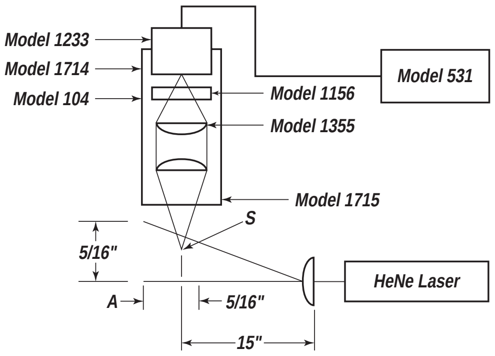
Sensing the position of macroscopic objects.

Sensing Displacement of a Wire

Position sensing detectors are often used in measurement situations where the sample is too delicate, small, or unsuited to contact measurements. In this example, the position of a 0.010-inch diameter wire is determined in one dimension. The location information may be useful to servo-control equipment such as wire take-up reels.

The light source is a 2 mW helium-neon laser, and its beam is expanded into a fan of light by a 25 mm focal length cylindrical lens. This fan is 5/16 inch wide by the time it arrives 15 inches away at the sample. A higher intensity light source can be used or the light source area coverage can be reduced to increase the signal level and the resolution. Though the sample in this case is a wire, anything similar in shape and size will produce about the same signal. For instance, the sample may be glass fiber from a fiber furnace, a thread, liquid stream, or a stream of solid particles.

The collection system consists of two short focal length lenses, and a 633 nm narrowband filter, which decreases interference from ambient light.



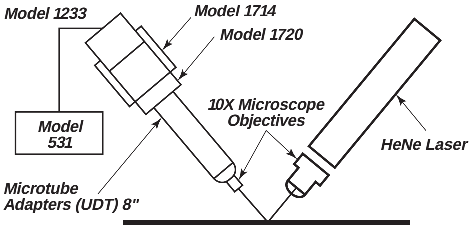
Sensing the small-scale displacement of a wire.

Profilometry

This is essentially a variation on the surface displacement measurement scheme discussed earlier.

A helium-neon laser or collimated laser diode is focused onto the test surface with a microscope objective. This provides the requisite small measurement spot. Then, another microscope objective images the reflected spot onto the position sensing detector.

The working distance, lens magnification, and test surface reflectivity all influence the system's overall profiling sensitivity.



Profilometry.