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Calibrating lateral-effect photodiodes for use as measuring devices in manufacturing

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Abstract

Lateral-effect photodiodes can be used as precision imaging sensors if their nonlinearity, as well as any distortion introduced by an optical system, is accounted for by a calibration procedure. Accuracies of 1 part in 1000, measured with respect to the field of view, are possible using commercially available sensors, camera bodies, and closed-circuit television lenses. Sensors that fall into this class of accuracy can be used to sense position in various industrial applications. An advantage over traditional, scanned sensors is the potential for rapid measurement rates.

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The lateral-effect photodiode

The lateral-effect present in all semiconductor junctions was first discovered by Schottky **[Sch30]** in 1930 and was then forgotten and rediscovered by Wallmark **[Wall56]** in 1956. As shown in Figure 1, lateral-effect refers to a photovoltage that appears *along*, as opposed to *across*, a semiconductor junction when it is illuminated by a nonuniform light source. The transverse photovoltage, appearing across the junction, is the basis of the common photodiode. That is, when a photodiode is illuminated, a photovoltage is produced across its terminals and a current flows. The lateral-effect also produces a photovoltage, but its intensity is related to the distribution of light on the semiconductor's surface.

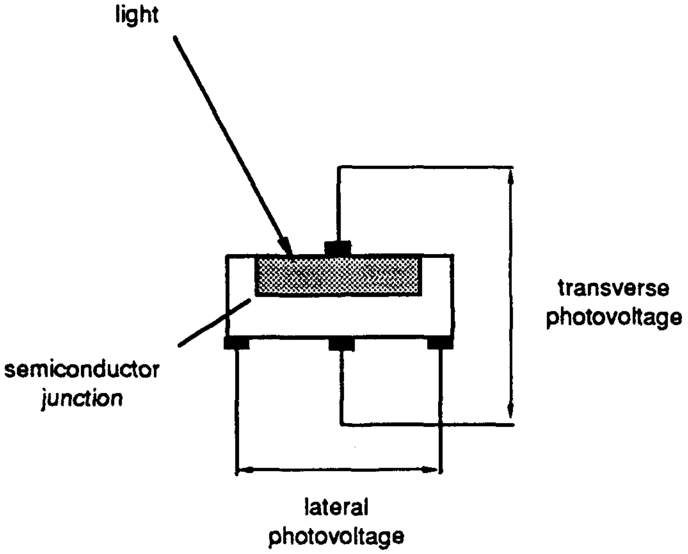

Figure 1. When light strikes the surface of a semiconductor junction, two voltages are induced: a transverse voltage that is commonly used to detect light and a lateral voltage that is not often exploited, but can be used to infer the position of the associated light spot.

Whereas the transverse photovoltage is primarily an indicator of a light source's power level, the lateral photovoltage can be related to the distribution of radiant energy on the semiconductor's surface. The work of Schottky and Wallmark demonstrated that a linear relationship exists between the lateral photovoltage and the location of a focused light spot. Wallmark also suggested that the effect could be exploited in a two-dimensional device by simply adding another pair of leads.

Wolltring **[Wol76]** provides a detailed model of both one and two-dimensional lateral-effect photodiodes. Several of his results are significant to practical applications of the device. Most importantly, he shows that multiple light sources result in a linear combination of photocurrents. Thus, the ever present noise source, ambient background light, simply adds to the photocurrent of a light source that represents a signal. This result is significant because it allows the effect of ambient light to be removed by a simple, linear operation. It also implies that defocusing is not a significant source of error. Given that the device is linear, if a light source produces a blurred spot, the photocurrents are related to the position of the light spot's centroid. Wolltring also suggested that variations in incident power can be rendered unimportant by a ratiometric technique. This involves expressing the light spot's location in terms of the difference in photovoltages along the junction divided by the total photovoltage. In other words, the computation of light spot position is normalized with respect to power.

Sensors based on the lateral-effect photodiode

A sensor based on the lateral-effect photodiode is essentially a camera. Typically, it consists of 3 components: First, a lens is required to focus a light source onto the image plane, which in this case, is the second component, a photodiode. A camera body completes the assembly by locating the photodiode with respect to the lens' optical axis. A schematic of such an assembly is shown in Figure 2. The light source is typically an infrared light emitting diode (LED) with a spectral density centered at 880nm.

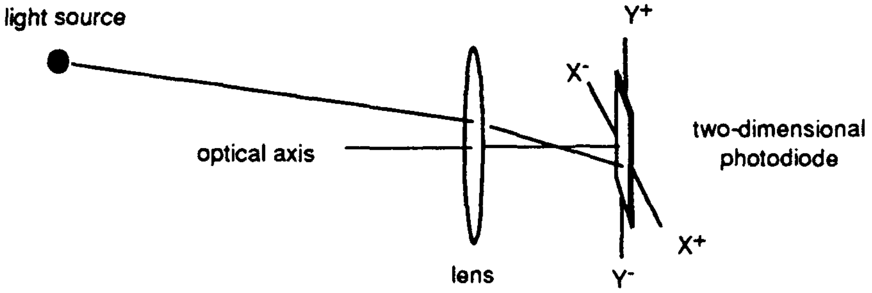

Figure 2. A typical sensor head using a two-dimensional, lateral-effect photodiode. A light source represents the signal to be measured. A lens focuses the light onto the photodiode's surface.

Commercially available sensors are available that exploit the lateral-effect **[Ham87]**. Both one and two-dimensional versions are available. One-dimensional products have sensitive areas that range from 3mm to 33mm in length. Two-dimensional versions can be as large as 22 x 22mm. Potential users must be critically aware of two specifications: position detection error and resolution.

Position detection error represents the difference between the actual position of the light spot's centroid and the predicted position. This concept is presented graphically in Figure 3.

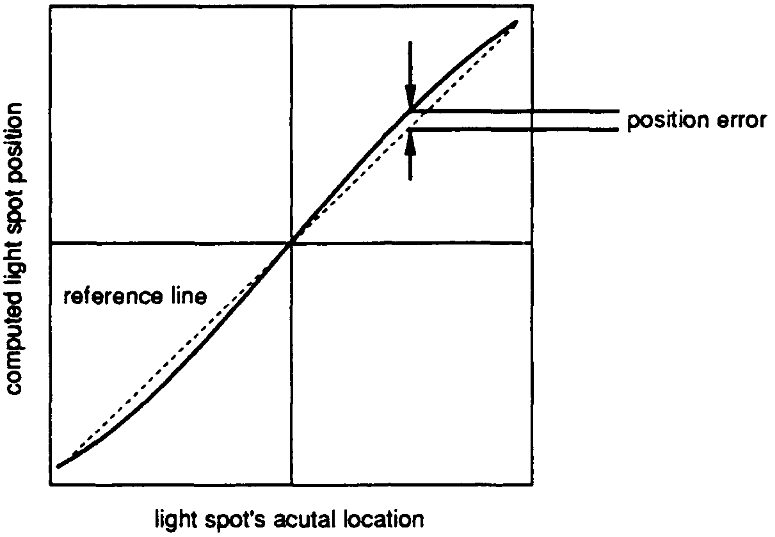

Figure 3. The relationship between light spot position and the photocurrents should be a straight line. In practice, a sizeable discrepancy exists.

For a two-dimensional sensor with a 10 x 10mm sensitive area, the error can be as large as 250 micrometers. This corresponds to an error of 1 part in 40. The error is systematic, however, and can be accounted for with a calibration scheme.

The resolution of a lateral-effect photodiode is much greater than its accuracy. For a typical, two-dimensional sensor with a sensitive area of 10 x 10mm, a light spot movement along the sensitive region of as little as 6 micrometers can be detected. This corresponds to a resolution of 1 part in 1600.

To relate this number to the movement of a light source, the focal length of the lens, as well as the distance separating the lens and the light source (i.e., object distance) must be considered. Referring to Figure 4, the first step is to determine the field of view (FOV). For the sake of simplicity, a thin lens model will be assumed. In practice, however, this is not sufficient and the principle plane locations must be known.

The field of view is related to similar triangles: one is formed by the lens center and the photodiode extents, the other is formed by the object distance and the field of view's border. Given the field of view, the light spot movement that can be resolved is directly related to the sensor's resolution.

That is, the field of view's width is divided by 1600 to determine the minimum detectable movement of the light source. For a lens with a 50mm focal length, an object distance of 5000mm, and a photodiode with a sensitive width of 10mm, the field of view is 1,000mm wide. 1/1600th of this width yields a resolution of .625mm. Thus, if a light source is attached to a moving object, a motion of .625mm can be detected by the sensor. Smaller movements will be unnoticed.

Unfortunately, the sensor's ability to accurately predict the object's absolute location in space is severely degraded by the position detection error that was mentioned earlier. Given that this error can be 1 part in 40, a discrepancy of 1000mm/40 = 25mm could exist in a given measurement.

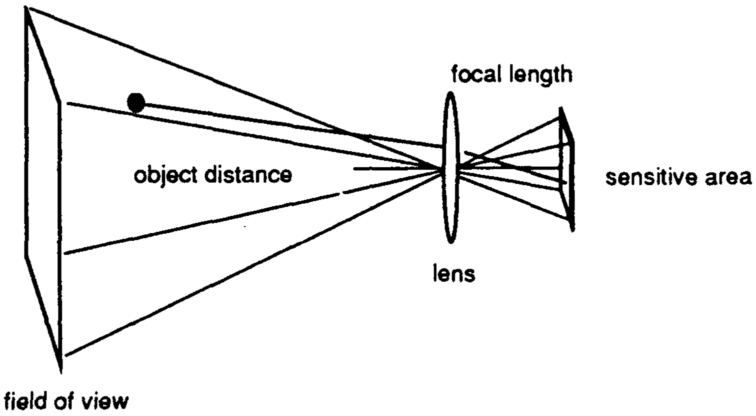

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Figure 4. The sensor's field of view is related to the photodiode's sensitive area, the lens parameters, and the object distance. It is common for the distance between the lens and the photodiode surface to be equal to the lens' focal length.

Applications

Because the lateral-effect photodiode is not a true imaging device, it will not be applied in areas normally associated with industrial image processing. In terms of capability, it is more closely related to the charge coupled device (CCD) linear array **[Cro90]** and will be used as either a position sensing or gauging instrument.

Linear arrays have several important uses in industry that involve a non-contacting measurement of position. Often a continuous flow process is involved. Steel manufacturers use linear array sensors to measure the widths of ingots. Textile manufacturers use linear arrays to measure yarn package diameter, yarn and thread diameter, webb position, and carpet thickness **[Crow90]**.

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In general, the linear array sensor is used to detect an edge, or pair of edges, that indicate width. The lateral effect photodiode cannot be used in a similar manner. However, in other applications where the linear array is used to measure height, the lateral-effect photodiode may offer an advantage. Consider the scenario shown in Figure 5: an imaging sensor is used to measure carpet thickness.

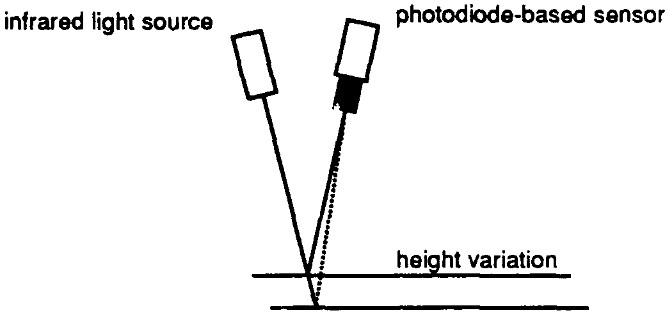

Figure 5. The location of the light spot is related to the height of the reflective surface.

Because the lateral-effect photodiode directly measures the position of the light spot's centroid, the computational procedure required with a CCD array to find two edges is unnecessary. Resolution and accuracy will be similar with either device. This inherent advantage also allows the photodiode to be considered for applications unsuitable to linear arrays.

The more general case of object position measurement is where the photodiode has a clear advantage. If an infrared emmitting diode can be placed on an object whose position is to be determined, an optical sensor using the lateral-effect diode provides an interesting alternative to other proximity-sensing technologies. Furthermore, if multiple emitters can be tolerated, the complete position and orientation of the moving object can be computed **[Ant89]**. In a manufacturing environment, this capability could be used to measure the location of automatic guided vehicles, pallets, and even people.

Figure 6 shows a conceptual AGV guidance system using lateral effect photodiodes as image sensors. Multiple LEDs are mounted in a suspended ceiling. They are arranged in a grid, with the grid spacing dependent on ceiling height. One or more sensors are mounted on the AGV. By imaging 3 or more LEDs, the position and orientation of the AGV can be computed. This concept is currently being used in the Department of Computer Science at the University of North Carolina to measure head position in a development project involving head-mounted display systems.

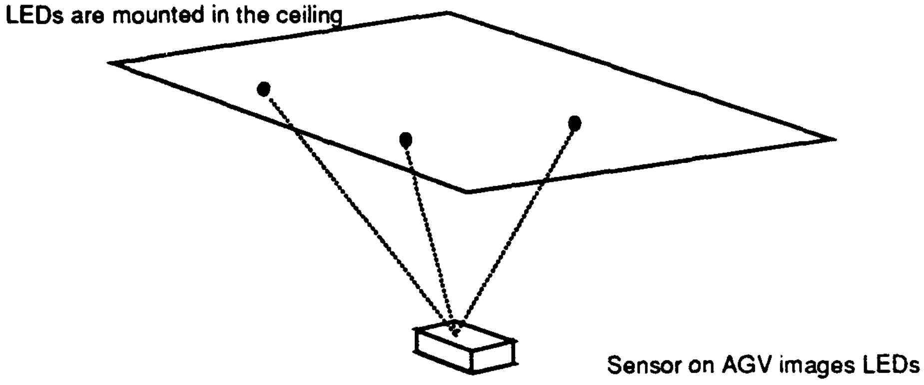

Figure 6. Computing the location of an AGV by imaging beacon locations with a sensor mounted onboard the vehicle. This scheme has been used to measure head position by Wang et. al.**[Wang 90]**.

The need for calibration

The possibility of an error whose magnitude is 1 part in 40 renders the lateral-effect diode virtually useless as a gauge. However, because this error is systematic, the device's resolution of 1 part in 1600 leads one to believe that increased accuracy can be achieved through calibration.

Calibration involves associating the actual light spot position with information emerging from the sensor that is corrupted by a systematic bias. A considerable body of knowledge in the field of photogrammetry **[Wolf83]** addresses this problem. Of particular relevance to users of industrial imaging equipment is research in the area of photogrammetry using non-metric lenses **[Fai76]** (i.e., photographic grade lenses). This work grew out of the availability of high quality lenses for photography that are quite inexpensive.

As mentioned earlier, users of optical sensors must know the internal geometry of their camera. That is, the focal length, the location of the principle planes, and the location of the image plane. Such information is of little importance to the photographer and, consequently, is not closely toleranced by camera manufacturers. This forces the user to determine each parameter via experimentation.

Experiments are usually designed to determine a model of lens distortion, as well. Distortion is a systematic source of error present in any optical system and can be corrected by calibration. Typically, a lens will exhibit pin-cushion distortion. The image of a square will appear as a pin-cushion. Models of lens distortion are often polynomials in r, the radial distance from the optical axis.

For photogrammety using film, a model that embodies the internal geometry and lens distortion is sufficient. The user of lateral-effect photodiodes must do additional work and add terms that account for position detection error. Such an experimental model has been derived by Antonsson[**Ant89**] at the MIT Biomechanics laboratory. His team was able to construct a camera model with a reported accuracy of 1 part in 1000. This seems to agree with the upper limit on resolution of 1 part in 1600.

The calibration procedure involves a mechanical actuator and a data collection system. The actuator is used to precisely index an infrared emitting light source. For each light source position, a snapshot is taken with the sensor and the data is stored for off-line processing. The goal of the off-line data analysis is to determine the coefficients of a high-order camera model using least-squares techniques.

Conclusion

The lateral-effect photodiode is an often ignored sensor. In certain applications, it is easier to apply and faster than the traditional CCD matrix or array. Particularly when an application involves the imaging of an infrared LED, the photodiode is the optimum choice because it rapidly measures the centroid of the imaged light spot. This characteristic makes it very easy to construct position measuring equipment that is both accurate and has a high update rate. The sensor head, i.e., camera body, lens, and photodiode, must be calibrated as a unit, however, for measurement applications requiring precision.

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