Conferencia invitada / Invited lecture

Laser beam spot centroid detection and tracking: technological basis and a few applications

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ABSTRACT:
A Continuous Position Detector (CPD) is used to determine the position of the laser beam spot centroid. Comparison between CPD and CCD performances are analyzed. The light tracking instrument developed is introduced. Various applications of CPD light tracker are described.

Key words: CPD, CCD, Light tracker instrument, Light tracker applications.

REFERENCES


1.- Introduction

A Continuous Position Detector (CPD) is used to determine the position of the laser beam spot centroid when impinging over its working area. The same information can be obtained with a CCD (Charge Coupled Device), identifying which of its pixels are being illuminated by that same beam and then applying an appropriate algorithm to process the recorded information. Even if, in this case, both devices match the requirements, the different technological basis used in each of them, establish a range of applications which define, according with the authors experience, the superiority of the CPD over the CCD.

The CPD consists in a common photodiode, where its anode is divided in four parts and driven back to the sides, leaving the intrinsic material exposed to the incident light. The photo-conductive semiconductor converts the incident light in electronic current collected by these four anodes. The magnitudes of these currents depend on the position of the spot centroid over the detector. Therefore, if the position of the center of the spot coincides with the center of the detector, the currents on the four output anodes will be the same.

The main operative and electrical characteristics of a CPD (UDT, model PIN-SC-10), are:

- Continuous Position Detection in the entire surface.
- Sensibility to the change of position: 2.5 μm.
- Precision independent the size of the spot.
- Simultaneous indication of position and power level.
- Spectral range: 350 – 1100 nm.
- Sensibility-radiation- (λ, pico, Vbias =10V) : 0.35 A/W.
- Sensibility-position-(λ, pico) : 0.4 A/W/cm.
- Linearity-position-(central 25%): 0.5%.
- Linearity-position-(central 75%): 4.0%.
- Derive for null point: 2 μm/°C.
- Dark current: 0.5 μA.
- Resistance series: 5 kΩ.
- Rise-time (10%-90%, Vbias =10V): 2 μs.
- Down-time (90%-10%, Vbias = 10V): 2 μs.
- Maximum working frequency (Vbias = 10V): 10 kHz.
- Approximate saturation level: 10 mW/cm2.

Two aspects of the latter description must be emphasized: a) CPD is not a classical quadrant detector where each individual diode must be illuminated to assure a correct indication of the position of the light spot, and b) the maximum working frequency is 10 kHz and it will be decisive, in some aspects, when compared it with a CCD.

The CCD is an analogical integrated circuit, which converts an optical image in an electronic signal. It consists in a series of Photo Metal-Oxide Semiconductors elements, arranged as 2D matrix, that basically compliment three functions: a) photoelectric conversion, b) charge storage and c) charge transmission to its associated electronic circuitry. Each one of these elements constitutes a pixel of the device. The electric signal output contains in a temporal sequence the information of the quantity of light received by each pixel, ordered in rows.

The main operative and electric characteristics of a CCD camera (SONY, model XCD-X710), are:

- Imaging Device: ½” Progressive Scan CCD.
- Pixels (HxV): 1024 x 768.
- Pixel Size: 4.65 x 4.65 μm.
- Sensing Area (HxV): 4.8 x 3.6 mm.
- Pixel Depth: 8 bit.
- Frame Rate: 30/15/7.5/1.875 fps.
- Electronic Shutter Speed: 1/100000 – 17.5 s.

A comparison of the characteristics of both devices in terms of the determination of the centroid position of a laser beam spot are shown in Table I.

<table>
<thead>
<tr>
<th>Device</th>
<th>CPD</th>
<th>CCD</th>
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<tbody>
<tr>
<td>Sensible area [mm²]</td>
<td>10x10</td>
<td>4.8×3.6</td>
</tr>
<tr>
<td>Sensibility to change of position [μm]</td>
<td>2.5×2.5</td>
<td>4.65×4.65</td>
</tr>
<tr>
<td>Maximum working frequency [Hz]</td>
<td>10000</td>
<td>30</td>
</tr>
<tr>
<td>Typical price [US$]</td>
<td>100</td>
<td>2000</td>
</tr>
</tbody>
</table>

Attending the four variables at Table I, CPD results more convenient than CCD. Moreover, the maximum work frequency that reaches a comparative rate grater than 300 to 1, is extremely important to track high speed displacements of laser beam spot centroid or displacements which include components whose frequencies are higher than a few Hertz.

2.- CPD and laser beam spot centroid tracking

A CPD is often employed to determine the position of the laser beam spot centroid over an active area of the order of 10 cm². To track the centroid through areas larger than 10 cm², a light tracking instrument was developed. The concept of light tracking essentially implies to avoid the beam to impinge outside the active area of the detector. Then, when the centroid of the spot approaches one of the edges, the detector is displaced according with the displacement of the laser spot. To perform this
operation the detector was mounted on the penholder of a plotter; its displacements were controlled from a PC. Its accurate mechanical steps were vectorial added to the indication of the detector to properly represent the coordinates of its trajectory X, Y on the plane.

Figure 1 schematically describes the light tracker instrument.

Output currents at the four channels of CPD are related with a pair of coordinates X, Y corresponding to the position of the center of the spot with respect to the geometric center of the detector. The four currents measured, called $X_1$, $X_2$, $Y_1$ and $Y_2$, vary according with the proximity to the respective edges of the detector. To determine the centroid coordinates X, Y the following algorithm is applied:

\[
X = \frac{(X_1-X_2)}{(X_1+X_2)} \quad (1)
\]

\[
Y = \frac{(Y_1-Y_2)}{(Y_1+Y_2)} \quad (2)
\]

Figure 2 shows the measured values of $X_1$ and $X_2$ according with the position of the centroid beam over the detecting area; the intensity of the beam was 50% of the saturation level of the detector.

Curves at Figure 2 are exponential functions between geometrical positions and voltages, and then the coordinates X, Y of the spot centroid are represented by hyperbolic tangents functions. So, the final electrical indication results in an almost straight line as a function of the position. Such electrical indications are multiplied by proportional factors to obtain metric coordinates expressed in µm.

The capacity to track the laser beam spot centroid was experimentally demonstrated by using a Router machine. Electrical step motors move its head along X, Y, and Z axis at ± 12.5 µm accuracy. A He-Ne laser was attached to the head and displaced along a CAD/CAM programmed trajectory on the X,Y plane that represents the cursive handwriting acronym “CIOp”. The light tracking instrument exactly followed the trajectory as it can be seen in Figure 3(a).

To evaluate the instrument performance a linear regression study over the diagonal that appears in Figure 3(a) was applied; results of this adjustment and the calculation of the residue or difference between the programmed and the measured straight line are shown in Figure 3(b).
3.- CPD in the study of retardation plates

A retardation plate is build-up from a uniaxial birefringent crystal. The crystal is cut so that the optical axis lies in a plane parallel to a face of the plate. A beam of unpolarized light normally incident on the plate is resolved in two perpendicular linear polarized components traveling with the same velocity along the optical axis, but with different velocities along a direction perpendicular to it. In this case emerging beams from the plate are out of phase. Plates where the phase difference between both beams is 45º are called quarter wave plates. Plates where the out of phase between beams is 90º are called half wave plates.

Retardation plates are used in different type of experiments and in many of them they are rotated around their geometrical axis to change the configuration of the polarized light in the experimental set up. Then in the specification quality of retardation plates could be include that the light traveling through them will maintain the propagation direction in spite of the fact that plates rotate. Simple experiments were performed to measure that property. A 5 mW CW red He-Ne laser was mounted in one end of a 5 m optical bench, while in the opposite end was installed the CPD light tracker. At 1.75 m from the detector ½\(\lambda\) and ¼\(\lambda\) retardation plates were mounted in a clamp that allows rotating them around the laser beam. In both cases the laser beam spot centroid describes a close curve. Figures 4(a) and 4(b) show the trajectories described by the centroid along the essays.

In Figures 5(a) and 5(b) the radius of the circles at Figures 4(a) and 4(b) are represented for ½\(\lambda\) and ¼\(\lambda\) retardation plates, respectively.

The test results for the ¼\(\lambda\) retardation plates are affected by refractive and diffractive deviations produced on scratched zones. The central point in both experiments corresponds to the direct observation of the laser beam. The average angular deviation for the ¼\(\lambda\) retardation plate was 116.94 ± 33.16 μrad and for ½\(\lambda\) plate was 657.99 ± 29.67 μrad. As a conclusion, the CDP is a reliable device to determine angular deviations of a laser beam affected by a retardation plate. On a 5 m length standard optical bench the angular deviation uncertainty was less than ± 6 % to ¼\(\lambda\) retardation.
plate, while for the \( \frac{1}{2} \lambda \) plate it was less than \( \pm 0.6 \) %.
Finally, it was experimentally demonstrated that to perform the best measurement when retardation plates are rotated in the optical layout is convenient to test them again rotation before use.

A study of a laser beam wandering after traveling a turbulent air has shown that the two perpendicular coordinates \( X(t) \) and \( Y(t) \) can be modeled as independent fractional Brownian motion (fBm). The Hurst exponent \( H \) that quantify the self-similarity of a process is sensitive to the mean flow of the warm air. So, it changes with different degrees of turbulence strength. Experimental measures were performed in the laboratory by creating convective turbulence with electrical heaters. Position fluctuations of a CW 10 mW red He-Ne laser beam spot centroid were recorded with the light tracker located as a screen at the end of the optical path. Figure 6 shows samples of spatio-temporal evolution traces obtained from the centroid position for three turbulence levels. The dispersion associated to each trace clearly grows with the turbulence strength and consequently its fractal dimension can be determined.

4.- CPD and the study of laser beam wandering in a turbulent air

When, by the end of 1999, to characterize the air turbulence provoked by electric heating devices begun at CIOp, the few groups that made efforts in that sense, in various parts of the world, used testing speeds of the laser beam position of about 300 samples per second. That poses the question as if that testing speed had not been adopted because it was usual to analyze the wandering phenomenon in the framework of Geometric Optics and to consider it as a markovian movement. In that case, that velocity assured that the successive data would not keep temporal correlation among them, which lead to introduce an appropriate covariance function to express the fluctuations of the refraction index. With the purpose to go deeper in this matter it was decided to rise as much as possible the recording velocity of the signal, reaching almost 1000 samples per second. This simple experimental strategy gave very interesting results [3-6].
Table II

<table>
<thead>
<tr>
<th>Turbulence</th>
<th>OSE$^2$</th>
<th>AOSE</th>
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</thead>
<tbody>
<tr>
<td>Normal</td>
<td>1.4381</td>
<td>0.0631</td>
</tr>
<tr>
<td>Soft</td>
<td>1.5744</td>
<td>0.0110</td>
</tr>
<tr>
<td>Hard</td>
<td>1.6437</td>
<td>0.0207</td>
</tr>
</tbody>
</table>

5.- CPD and the analysis of large building structures

The CPD was employed to determine the position of the laser beam spot centroid over its active area in observations of large building structures as the Cathedral of La Plata, La Plata, Argentina, and the “Jorge Sahade” astronomical telescope located in the Complejo Astronómico el Leoncito” (CASLEO), in the central west mountain district of San Juan, Argentina, near the Andes. To avoid the natural divergence of laser beam because the distances of observation, the red He-Ne laser beam was projected by a Keplerian telescope, while in the observatory a Galilean telescope was employed. Measurements in La Plata cathedral were performed in the tower in which a tourist elevator is installed; the laser system was placed at the bottom of the tower and the light tracker instrument 68 m above. Observations in the “Jorge Sahade” dome were performed outside the optical axe of the telescope; the laser system was placed at the top, on a working platform 20 m above the light tracker instrument. Figure 7(a) shows a front view of the La Plata “brick” cathedral; Observations were performed inside the left tower. Figure 7(b) describe a typical result of an observation session [8]. Figure 8(a) shows the main building where the “Jorge Sahade” astronomical telescope is installed. Figure 8(b) describe a typical result of an observation session [9]. At first sight it could be concluded that inside the cathedral tower the observations reveals air turbulence, while inside the dome of the telescope a tiny mechanical drift could be present.

Acknowledgments

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