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3-D Measurement by Dual Four-Quadrant Position-Sensitive Detectors in the Stereo Mode

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ABSTRACT
This paper focuses on 2-D position sensitive detectors based on four-quadrant (4Q) photodetector. In normal operation, one of these detectors can measure lateral displacement at x and y dimensions. By using dual of these detectors and dual optic for them and comparing the output signals, third dimension (z-axis) can be also measured. In this paper fundamental and calculation of this measurement method is investigated and simulated.

Keywords - **Four quadrant (4Q), position-sensitive detector (PSD), lateral displacement**

I. INTRODUCTION

Four-quadrant detectors consist of quad cells that positioned symmetrically around the geometric center of the sensor. The narrow gaps separate these four photodiodes. Any of these photodiodes converts the related incident light energy to photocurrent signal. By comparing output signals of this detector, two-dimensional position would be achievable for incident spot light. Thus, any four-quadrant detector can measure noncontact lateral displacement which takes place in the parallel plane respect to the active surface of detector. Four-quadrant PSDs can measure the center of incident light profile and in this condition any of photodiodes generates similar photocurrent signals, because each photodiode receives equal light power.

When the spot light or image of target moves over the detector surface, each photodiode receives different light power so that output signals change. The advantages of 4Q-PSD are its continuous output signal, higher speed response, and more circuit simplicity, comparing the digital pixel detection methods. But its disadvantages are dependence to contrast and shape of the incident spot light and also disability to recognizing two targets [1].

Also, 4Q-PSD based sensors more be used in center detecting applications such as laser beam alignment and optical tracking systems. In this paper it is demonstrated that for distance measuring with dual of these detectors, center of the 4Q detector must be slightly out of the optical axis of the lens. By this condition and by increasing the target distance, the target image on the detector surface would be closer to the center of this image, thus analog output signals would be changed. At this condition the measuring of lateral displacement of this detector fails, and consequently, by using one of these detectors, we can't measure the distance and lateral displacement simultaneously.

For solving this problem, dual of these sensors in the stereo mode can be used. One advantage of this method respect to triangulation method and other cases for distance measurement is more simplicity in processing method and implementation [7-8]. By this method lateral displacement can be measured only by use of two 4Q-PSDs. One usage of this method can be introduced for free space optic communication (FSO) that straight trajectory laser beam is used for transmission channel instead of optical fiber channel. In transmitter the laser source is modulated and in the optical receiver one photodiode for receiving laser energy and 4Q-PSDs for dynamic adjusting line of sight between transmitter and receiver are utilized. Thus stereo 4Q method can be used for this case and distance measurement is useful for optimizing this adjustment.

II. GENERAL PROPERTIES OF THE FOCUSED 4Q RECEIVER

If the target itself be an active optic source like one laser diode, 4Q-PSD can directly detect its position. But for passive target, this detector needs an optical transceiver system to construct an image of target over the detector surface. This optic consists of a light source like LED or laser diode that illuminate object plane and one optic receiver that concentrate reflected lights from the target on the detector surface. By means of one positive lens, the receiver construct image of illuminated target over the quad cells. It is better to use sheet reflector or corner cube reflector (CCR) on the respective target to achieving good contrast, uniform intensity, and desired symmetrical image. For calculating the x and y position of the image spot, we can use following equations [2]:

$$u_x = K\frac{(i_a + i_d) - (i_b + i_c)}{i_a + i_b + i_c + i_d} \quad (1a)$$

$$u_y = K\frac{(i_a + i_b) - (i_c + i_d)}{i_a + i_b + i_c + i_d} \quad (1b)$$

In this equations, K is the slope factor and its value is dependent to size and shape of the image spot. Also i_a, i_b, i_c, and i_d are four current signals that produced by each photodiode. For square shape image, the transfer function between u_x and actual image x position is linear but by non uniform intensity profile or tilting square or rotating square image, this linearity would fail [3-5]. For circular image, this transfer function is inherently nonlinear but around the detector center is linear approximately, also this transfer function is like sigmoidal curve [6]. The slope factor (K) is proportional to the coefficient between u_x and processed current signals and for square shape image with narrow gaps in detector its value is $d/2$ and is $\pi d/8$ for circular image, where d is the side of square image or the diameter of circular image [2].

The size of the reflector image (target image) appoints the practical measurement span on the detector surface. When image edge reaches to the detector gaps, spot light drops only on one or two photodiodes thus the transfer function would be invalid. Because of the magnification of optic receiver, valid measurement span on the target plane is greater than respect to detector surface and equal to reflector size. If target distance changes respect to the sensor, the image size and image displacement also changes proportionally, thus measuring in lateral direction is independent of the target distance. The target displacement in the x axis is (A.Makynen, *et al*, 1995):

$$U_x = M\frac{d}{2}\frac{(i_a+i_d)+(i_b+i_c)}{i_a+i_b+i_c+i_d} = \frac{D}{2}\frac{(i_a+i_d)+(i_b+i_c)}{i_a+i_b+i_c+i_d} \quad (2)$$

where D is the reflector side, d is the side of the image, and M is the magnification of the optics receiver.

III. FUNDAMENTAL OF 3D MEASUREMENT BY DUAL 4Q PSD AND ARITHMETICAL EQUATIONS

The optical receiver of the measuring method is illustrated in Fig. 1. According to this figure two PSDs arranged at x axis and field of view illuminates by LED or laser diode optic source and reflected lights from this target make an image at the any sensitive surface of detectors. Because of mismatch between center of 4Q-PSD and optical axis of its lens, at the specific distance of the lens ($PS/2\Delta$), each image sit at the center of its detector in x direction coordinate, so the output signal of each PSD becomes zero at this point ($U_{x1}=U_{x2}=0$). At greater distances from this critical distance each image close to another, thus output signals become smaller than zero (negative sign for U_{x1} and U_{x2} output signals). For smaller distances respect to this critical distance each image moves toward far another, so the output signals become greater than zero (positive sign for U_{x1} and U_{x2} output signals). Lateral displacement measuring in the y axis is same to one of these sensors and for better result the average of two y-axis signals be calculated ($(U_{y1} + U_{y2})/2$). The lateral displacement in the x axis can be calculated by differencing between U_{x1} and U_{x2} signals. All equations relating to this measuring method are as below:

$$U_{y1} = U_{y2} = \frac{Y}{D} \quad (3)$$

$$U_{x1} = \frac{\left(\frac{S}{2} - \frac{R\Delta}{P}\right) + X}{D} \quad (4)$$

$$U_{x2} = \frac{\left(\frac{S}{2} - \frac{R\Delta}{P}\right) - X}{D} \quad (5)$$

$$X_{signal} = \frac{D}{2}\left(U_{x1} - U_{x2}\right) \quad (6)$$

$$Y_{signal} = \frac{1}{2}\left(U_{y1} + U_{y2}\right) \quad (7)$$

$$Distance = Z_{signal} = \frac{P\,(S - D(U_{x1} + U_{x2}))}{2\Delta} \quad (8)$$

$$R_{critical} = \frac{PS}{2\Delta} \quad (9)$$

In these equations X, Y, and Z are real displacement of target in the 3-axis and X_{signal}, Y_{signal}, and Z_{signal} are the calculated and related signals of them. D is the half of target diameter, S is the distance between two PSDs, R is the distance of target from lens, P is the image distance to lens (effective focal length), and Δ is the distance of mismatch between PSD center and receiver lens axis. Acceptable measurement range of this method is defined by following equations as is depicted in Fig. 2. According to this figure, maximum lateral displacement in the x-axis is obtained at the critical distance because at this point images of reflector sit exactly at center of every PSDs and valid displacement in any direction is equal to D (half of target diameter). At R_{max} distance, lateral displacement is also limited to zero.

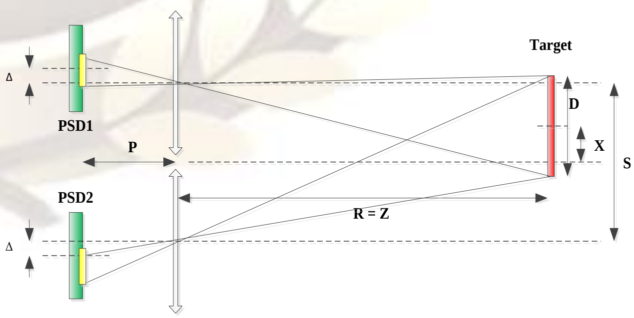


Fig. 1. Two 4Q-PSD and optic of them in the stereo mode.

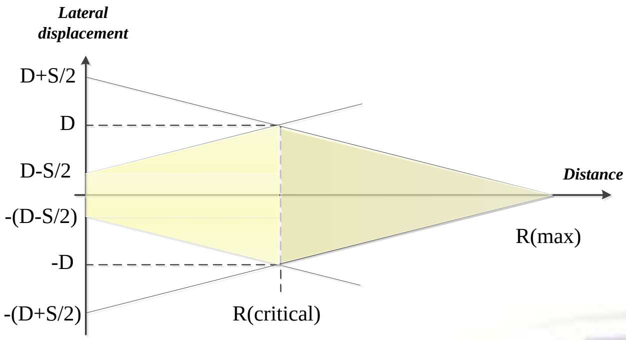


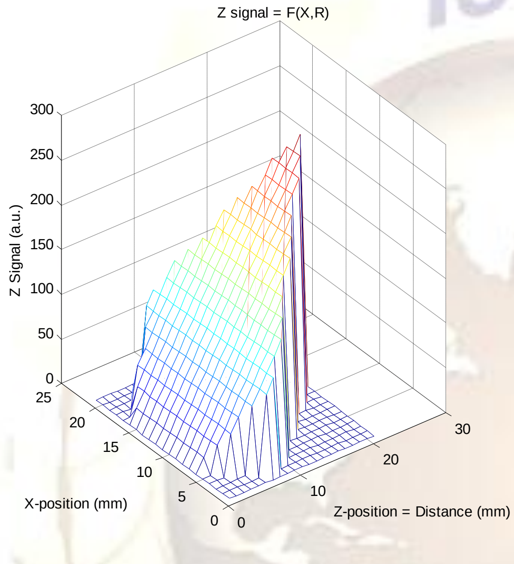
Fig. 2. Acceptable span for measuring at x-z plane.

$$R_{max} = \frac{P\left(D + \frac{S}{2}\right)}{\Delta} \tag{10}$$

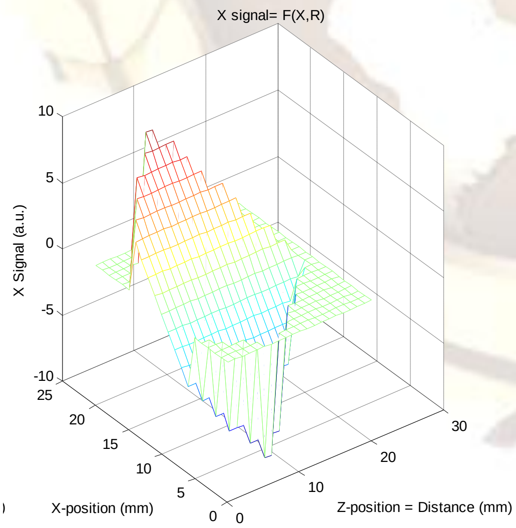
$$-\frac{D}{2} < Y < +\frac{D}{2} \tag{11}$$

$$-\left(D - \frac{S}{2} + \frac{R\Delta}{P}\right) < X < +\left(D - \frac{S}{2} + \frac{R\Delta}{P}\right) \text{ for } (R<R_{critical}) \tag{12}$$

$$-\left(D + \frac{S}{2} - \frac{R\Delta}{P}\right) < X < +\left(D + \frac{S}{2} - \frac{R\Delta}{P}\right) \text{ for } (R>R_{critical}) \tag{13}$$



(a)



(b)

Fig. 3. (a) Z_{signal} and (b) X_{signal} graphs for square shape spot light.

IV. SIMULATION RESULTS

Measurement in the x and z axes are simulated by transfer function of them simultaneously in the MATLAB and then two 3-D graphs of X_{signal} and Z_{signal} are depicted. One simulation is executed for square target and another is executed for circular target. The simulation results are respectively shown in Fig. 3 and Fig. 4 for square and circular shapes. Output signal of each 4Q-PSD is obtaining by follow equations:

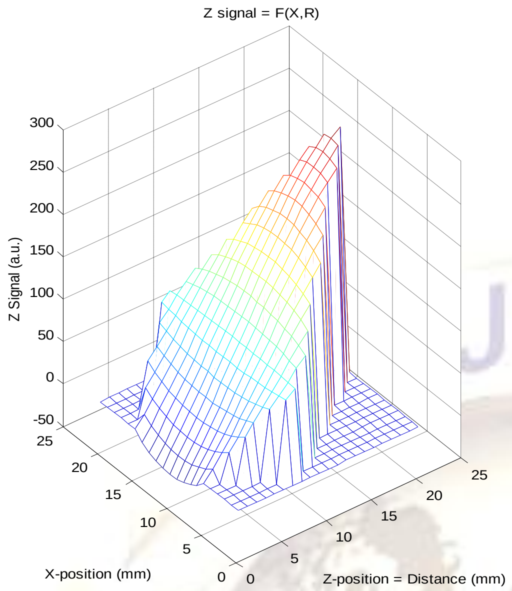
$$u_x(PSD1) = \frac{2}{\pi}\left[\sin^{-1}\left(\frac{\left(\frac{S}{2} - \frac{R\Delta}{P}\right)+X}{D}\right) + \left(\frac{\left(\frac{S}{2} - \frac{R\Delta}{P}\right)+X}{D}\right)\sqrt{1 - \left(\frac{\left(\frac{S}{2} - \frac{R\Delta}{P}\right)+X}{D}\right)^2}\,\right] \tag{14}$$

$$u_x(PSD2) = \frac{2}{\pi}\left[\sin^{-1}\left(\frac{\left(\frac{S}{2} - \frac{R\Delta}{P}\right)-X}{D}\right) + \left(\frac{\left(\frac{S}{2} - \frac{R\Delta}{P}\right)-X}{D}\right)\sqrt{1 - \left(\frac{\left(\frac{S}{2} - \frac{R\Delta}{P}\right)-X}{D}\right)^2}\,\right] \tag{15}$$

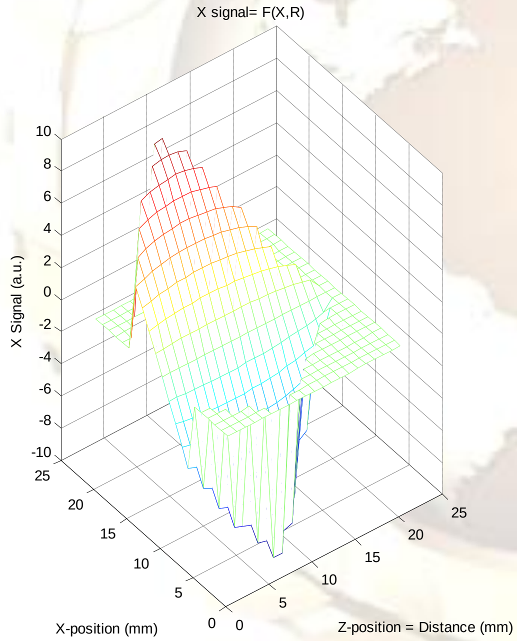
The nonlinearity errors for lateral displacement (x-axis) in the stereo and mono 4Q-PSD methods are respectively shown in Fig. 5(a) and 5(b). According to the figure, the inherent nonlinearity correspond to circular spot light is improved by using of dual 4Q-PSD instead of mono case. These graphs show that maximum nonlinearity errors are 0.04 and 0.05 for stereo and mono methods, respectively.

V. CONCLUSION

A method for simultaneously measurement of lateral displacement and distance of the target has been proposed. The sensor includes two stationary transceivers and a lightweight reflector fixed to the target. The lateral position of the reflector with respect to the optical axis of the system is measured by calculating difference between output signals of two PSDs and the distance position of the target is measured by calculating summation of these two output signals. The simulation results show that responses for square target is perfectly linear and variation of x and z positions are independent respect to each of other while response for circular target is nonlinear and x and z positions are dependent together. Also, it has been revealed that the linearity of the stereo 4Q-PSDs measurement is better compared to the mono mode.

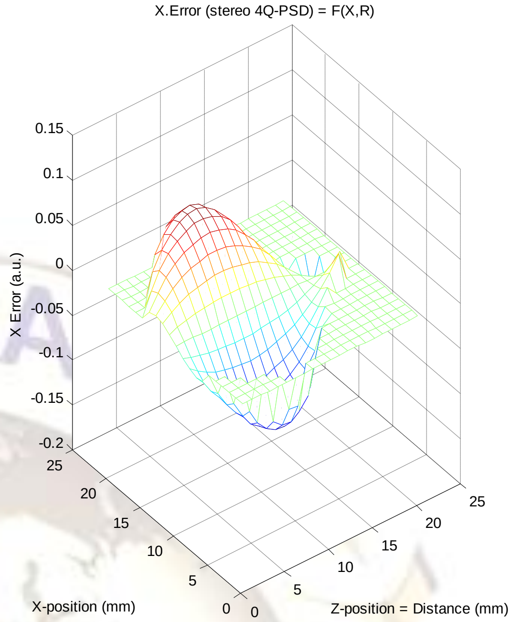


(a)

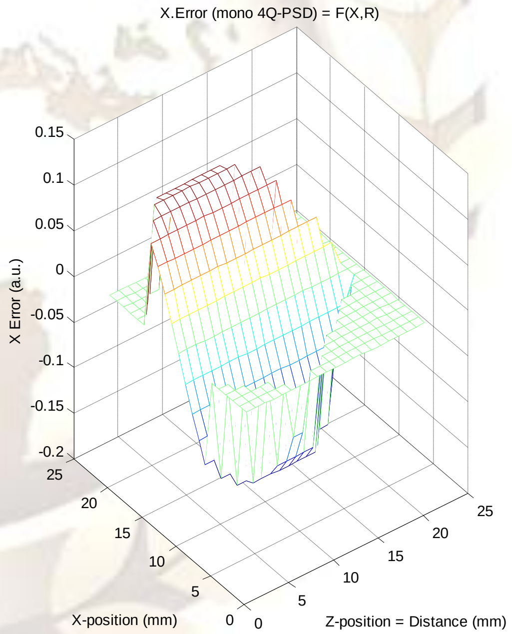


(b)

Fig. 4. (a) Z_{signal} and (b) X_{signal} graphs for circular shape spot light.



(a)



(b)

Fig. 5. The nonlinearity in X_{signal} for (a) stereo and (b) mono.

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