Analysis and Improvement of the Position Nonlinearity in Lateral Type Position Sensitive Detectors

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Abstract—Optical position-sensitive detectors are simple photodiodes capable of detecting the centroid position of a light spot projected on their surface. The position information is calculated from the relative magnitudes of a few photocurrent signals provided by the PSD. In a quadrant detector (QD),photocurrents are derived by projecting a light spot on four photodiodes placed close to each other on a common substrate, while thelateral effectphotodiode(LEP)isasinglephotodiodeinwhichembedded resistive layers are used to generate the position-sensitive signal currents. The linearity of a lateral effect PSD mainly depends on the quality of the active area. The p-n junction PSD is designed with a p-doped layer and the MOS PSD with a channel which will act as a current divider for the generated photo current. Uneven resistivity over the active area of the PSD will also result in an uneven distribution of the generated photo current and thus cause an error in the determined position. The quality and uniformity of the active layer of the PSD is determined duringthe manufacturing process. Thus accurate, high quality processing is the first and most important step when manufacturing high linearityPSDs.

Index Terms—position sensitive detectors, PSD, nonlinearity, photocurrents.

I. Background

PSDs are widely used in commercial and industrial ap- plications where low-cost or high-speed position sensing is needed. LEPs are probably mostly used in optical distance meters based on the triangulation principle [1]. Such sensors are used in various kinds of height, thickness and vibration measurements needed in industrial fabrication processes, for example, as well as in inexpensive cameras to provide the target distance for the autofocus mechanism [2][3]. In addition to distance measurements, triangulating sensors are used for switching various domestic devices such as electric fans, air conditioners, water taps and sanitary facilities on and off by detecting the presence of a human body [2][3][4]. Other applications include miscellaneous types of position, motion, vibration, alignment, levelling and angle measurements and beam tracking applications [5][6][7]. QDs are mostly used as centring indicators rather than as linear position sensors. Large quantities of them are used in CD-ROMs and audio players, for example, to centre and focus the pick-up laser beam on the disc track to be read [8]. Other uses include various kinds of precision instrumentation and robotic, military and aerospace tracking applications [9][10][11]. Imaging detectors such as CCDs are sometimes used for light spot position sensing instead of PSDs, particularly in instrumentation applications requiring the utmost accuracy and sensitivity. It is obvious that the mass production of low-cost CMOS imagers and the rapid development of digital signal processing ICs together will partially replace PSDs in some of the traditional applications described above. It should be noted, however, that it is not easy to replace a two-dimensional PSD with an imaging detector in applications where the measurement speed exceeds the standard video frame rate or where a low signal processing load (low power consumption) is required [14]. The sensors presented in the present paper belong to this category.

The reflected beam sensors proposed in this paper are in principle similar to the laser spot trackers used in aerospace and military applications, which use active illumination and a misfocused QD receiver to measure the angular displacement of a laser spot from the optical axis of the receiver. Receiver misfocusing is needed to enlarge the tracking FOV and conse- quently to maintain continuous, stable tracking [12]. Similar techniques have also been experimented with for geophysical measurements [13].

In this paper, a tracking sensor is implemented for a 3D coordinate meter in order to point its measurement beam automatically towards a marked point on the object surface. A practical sensor implementation based on a focused QD re- ceiver, coaxial illumination and a small sheet reflector provides comparable accuracy with manual aiming when the object to be measured has diffuse reflectance properties. The practical operating environment may also include specularly reflecting objects, however, in which case sufficient tracking accuracy may not be achieved, due to strong background reflections. The polarisation filtering proposed for reducing this error has proved to be effective and technically feasible.

II. METHODS

A reflected beam sensor is composed of an optical transceiver and a reflector. The transmitter illuminates the mea- surement field with a uniform beam, the divergence theta of which equals the angular field-of-view (FOV) of the receiver, and the light reflected from the target is focused on the PSD located at the focal plane of the receiver optics.

A block diagram of a typical signal processing circuitry is depicted in Fig. 1. The illuminator (LED, laser diode etc.) is on/off-modulated in order to distinguish the signal from background illumination. The PSD provides four current signals the relative amplitudes of which are proportional to the light spot position on its surface. These current signals are amplified and their amplitudes detected using four iden- tical signal conditioning channels, each of which consists of a transimpedance preamplifier, postamplifier, synchronous demodulator and A/D converter. To cope with signal level variations, the postamplifier may include variable gain, or the transmitter power may be variable. Wang, C., et al. done a significant research on sensing noise mitigation andcalibration [15]. Here, the position calculation is performed numerically.

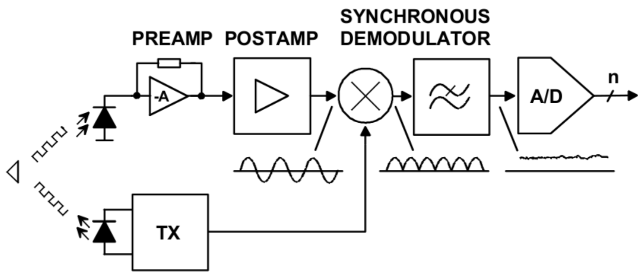

Fig. 1. Block diagram of the signal processing circuitry of a reflected beam sensor.

The position information is derived from the optical signal powers received by the quadrants the electrical contributionof which then serves to define the relative position of thelight spot with respect to the centre of the device. Ivan,I., et al. set the foundations of systems like this [16]. The contacts are positioned at the opposite edges of the sheets,and the contact pairs of the sheets are oriented perpendicularly to each other. The photon-generated current carriers divide between the contacts in proportion to the resistance of the current paths between the illuminated region and the contacts. The position of a light spot centroid can be deduced fromthe currents of the contact pairs, since the resistances are directly proportional to the lengths of the current paths [17]. Calculation of the spot position is based on the same principle in both cases: subtracting the opposite signals in the direction of the measured axis and dividing this result by the sum ofthe samesignals.

Despite the apparent similarity, there are two important differences that affect the properties of the PSDs, and consequently their suitability for different sensing applications. The first is the effect of spot size and shape on the extentof the measurement span and the behaviour of the lateral transfer characteristics within this span, andthesecondis the difference in their noise levels and correspondingly in the achievable precision[18].

A. *Limits of measurementaccuracy*

The limits for the measurement accuracy are set bythe achievable signal to noise ratio (SNR) and the reflector background contrast, defined as the ratio of the powers ofthe signals received from the reflector and theilluminated background. The former determines the achievable precision and the latter the lower bound for systematic errors.Also,the distortion errors have a significant effect on the PSD measurements. The distortion rectifying method introduced by Rahimi, M., et al. solved these problems and set the foundations for this paper and other similar works [19]. Meanwhile, the research of Rodiguez-Navarro,D.,etal.ontheerrors in calculation of the point of incidence on the PSD sensor surface introduced a complete error analysis for improvingthe measurement accuracy[20].

B. *PrecisionoftheLEPandQDreceivers*

The incremental sensitivity of the LEP and QD receivers depends on the lateral transfer characteristics and signal cur- rent distribution (head-or-tail-current v. head-and-tail current) of the PSDs, on noises originating from the PSDs,preamplifier and background, and on the noise correlation between signal channels. This has been investigated thoroughly by Dianyou, D., et al. [21]. The results of the analysis, including the above factors, are presented in this paper. First the relation between the SNR and precision is determined (noise sensitivity), and thenthedominatingnoisesourcesareevaluated,andfinallythe precisions of the LEP and QD receivers are compared under conditionsoflowandhighbackgroundillumination.

C. Predominant internal noisesources

The noise of the signal processing circuitry originates from the PSD and the transimpedance preamplifier, which is typically constructed using an operational amplifier (op amp)(Fig. 2). When properly designed, the op amp makes essentiallyno contribution to the total noise of the preamplifier, and if shot noise due to background illumination is also neglected, the main noise contributors are the thermal noise of the feedback resistance Rf in the case of the QD and that of the interelectrode resistance Rie in the case of the LEP [22].

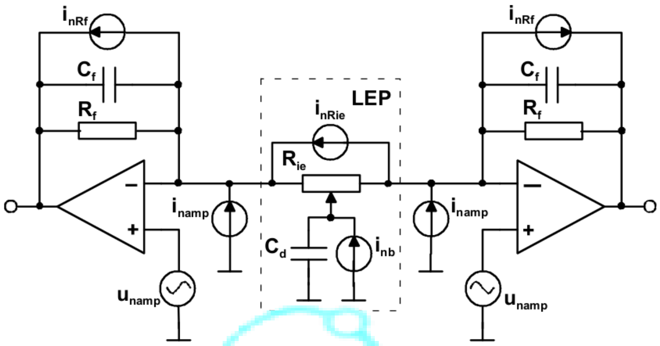

Fig. 2. Main noise sources of a LEP receiver.

The value of thefeedbackresistanceofaQDreceiveris basically fixed by the desired preamplifier bandwidth, the unity-gain bandwidth of the op amp and the photodiodecapacitance. The phase lag caused by the photodiode capacitanceis compensated for with the feedback capacitance to provide stable operation. The feedback capacitance then determines the bandwidth of the preamplifier together with the feedback resistance, and in this way fixes the value of the feedback resistance and the noise level accordingly. This has been extensively examined by Gugg,C., etal.[23].

III. ProposedSensor

The first sensor, comprising a focused QD receiver and asmall piece of sheet reflector, was developed for short-rangeindustrial tracking and displacement sensing applications. Thesecond sensor is composed of a focused LEP receiver and aCCR, and has been employed for aim point trajectory measurement in long-range shooting practice performed outdoors.In tracking applications no systematicerroris caused bythe background reflections as long as the background reflectivity is uniform, since the centroid positions of the reflectorimage and the background are the same [24]. A non-uniformbackground reflectivity causes error, however, which can beroughly approximated by assuming thatthehalf circles ofthe illuminated background (Lambertian) have different butuni form reflectivities. This has been discovered by outstanding works of Welch, D. et al. [25].

The operating principle of the pointing system resembles that of automated total stations. During measurement execu- tion the nominal coordinates included in the design database of the measured object are used to point the transceiver optics roughly towards the target, after which the tracking system is used to point the rangefinder beam accurately at the centre of a cooperative mark placed at the desired measurement point. The operating range depends on the application, varying typically from 3 to 30 m in assessing the manufacturing accuracy of ship blocks, for example. The pointing accuracy should be comparable to manual measurements, in which aiming accuracy comparable to or better than that provided by angle encoders is typically achieved. Thus automatic pointing should have an accuracy of better than 0.5 mm at 10 m, for example. Finally, the time needed for pointing should obviously be much shorter than that taken for manual aiming (about 30 s) and preferably short by comparison with that needed for the coordinate measurement itself (less than 5 s).

IV. SensorAccuracy

The reasoning behind the determination of an appropriate size for the tracking and acquisition FOVs and the reflector to fulfil the design goals are explained in here. Due to the stationary target, it is possible in principle to achieve stable and accurate pointing irrespective of the extent of the tracking FOV and the speed

of the servo system [26]. This means that misfocusing is not needed in order to adjust the size of the tracking FOV. The size of the acquisition FOV depends in turn on the search strategy and on the degree of positional uncertainty of the reflector being searched for. The principle used here for finding the reflector was simply to make the acquisition FOV large enough to cover this positional uncertainty when the receiver was pointed towards nominal reflector position. With ship block measurements, for example, the nominal coordinate values and the position of the actual mark typically differ a few cm at the most, which means that the acquisition field should cover a lateral field of a few micrometres throughout the operating range. The coordinate meter optics is shown in Fig. 3.
According to the above, a suitable combination of FOV and reflector size can readily be found to fulfil the design

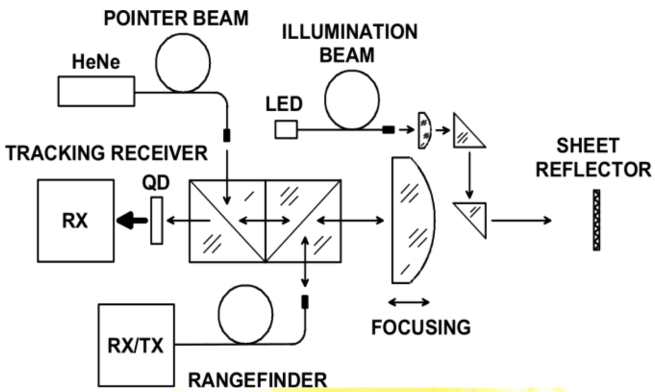

Fig. 3. The coordinate meter optics.

goal set for manufacturing accuracy control applications. The performance of the pointing system is also affected by the sensor construction, however, and by the various non-idealities of practical components.
Note also that the background of the reflective marks may not be diffuse but specular, and thus larger pointing errors than those predicted by the diffuse model are possible in practice.

V. Discussion

The principle proposed here provides a potential means for implementing high-speed 2D displacement sensors with micrometre precision. Unlike a conventional reflected beam sensor, it provides position information which is proportional to the linear rather than angular displacement, and scaling which is range-invariant and solely determined by the size of the reflector. This means that the stand-off distance can vary within a large range and that the measurement field of the sensor can be tuned for a particular measurement task simply by using a square-shaped reflector of known side length that is long enough to cover the amplitude range of the displacements to be measured. In practice, the extent of the measurement field can range from a few millimetres to several micrometres. Although, an adaptive local scanning method such as one introduced by Rahimi, M. et al. can significantly reduce the scanning time needed for the mentioned field [27]. The results of our works show that a sensor composed of standard components, having a measurement field of about 1 cm and using a stand-off distance of a few millimetres can provide a bandwidth of several kHz, a precision that is limited to the level of a few micrometres by noise fluctuations, an inherent scaling accuracy of a few % and integral non- linearity better than 1%. This confirms the similar findings by Xu, G. et al. [28]. Only relative coarse focusing and orienting of the reflector are needed when the sensor is set up. Accurate receiver focusing is not needed if oversized reflectors are used, and thus the simplest means of focus adjustment should be sufficient. This is based on the very interesting founding of Sun, Z. et al. [29]. It is also relatively easy to set up proper rotational orientation for a reflector using coaxial viewing optics with a suitable reticle, for example. However, Setting up the observation angle may prove somewhat more complicated, as shown by Liu, Y. et al. [30]. The main drawback concerning the practical performance of the proposed method was the powerful effect of noise fluctuations on the achievable preci- sion, which would have been one or two orders of magnitude better at a distance of a few micrometres without noise effects. Note, however, that since the spectrum of noise fluctuations is typically concentrated well below the 100 Hz region, it should be possible to measure vibratory displacements above 100 Hz with a precision determined by the electrical SNR simply by using high-pass filtering to remove the effect of noise fluctuations . Note also that averaging should provide an improvement in precision below the 100 Hz region if the measured displacement is repetitive. The displacement of a sinusoidally vibrating loudspeaker coil measured with the experimental sensor system from a distance of 2.5 um is presented in Fig. 4.

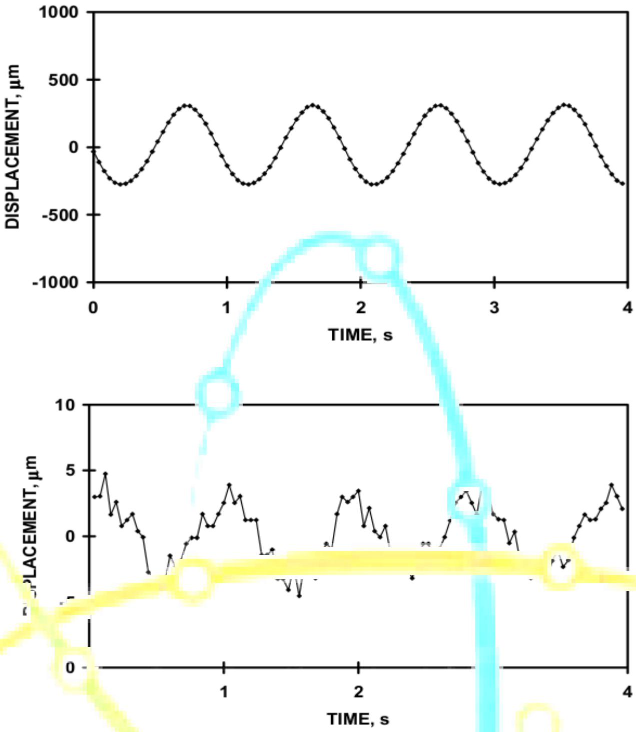

Fig. 4. Displacement of a sinusoidally vibrating signal measured with the experimental sensor system. No averaging or filtering was used to remove the effect of air currents.

The measured and calculated standard deviations in the case of one PSD and an accurately focused LEP receiver within a distance range from 50 to 300 mm are depicted in Fig. 5. The results obtained with a direct beam sensor are also included for a reference. The experimental results for the reflected beam sensor are approximately twice as inaccurate as those predicted before, and also 1.4 to 2.1 times worse than those for the direct beam sensor, although the calculations suggested that they should have been slightly better (about 20%). Only a small part of the difference between the measured and calculated values was estimated to be due to the non-idealities of the measurement setup. A possible explanation for the difference could be that the geometric optics formulation, which is based on the assumption of weak turbulence, gives results that are too optimistic under the intermediate turbulence regime representing the upper boundary of the validity range. Another possible reason is that beam wander off the receiver aperture occasionally reduces the effective aperture size and thus may well affect the angle-of-arrival variance observed at the receiver. This is result follows other research about this problem [31]. Comparison with other experimental results was not possible, since none seem to have been published before.

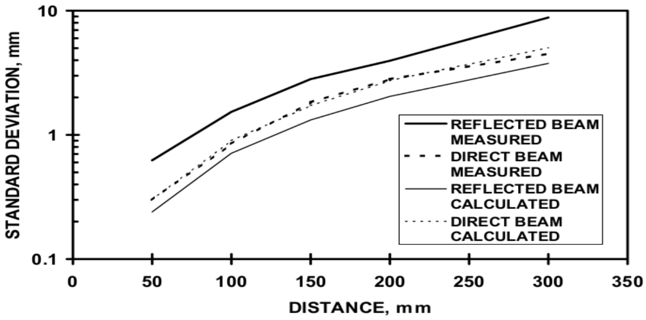

Fig. 5. Calculated and measured standard deviations in the lateral displacement results obtained with a direct beam sensor and a focused reflected beam sensor in intermediate noise turbulence.

The performance improvement factors and test results of the PSDs can then be summarised. The best candidates for long- range displacement sensing applications are the phototransistor PSD, tracking PSD and digital PSD. The tracking PSD pro- vided the best overall performance, with a 40-fold improve- ment in sensitivity and two-fold improvement in linearity over a LEP. The phototransistor PSD and the digital PSD provided 10-fold improvement in sensitivity along with equal or better linearity. Since the prototypes were designed without extensive optimisation, the performance reported is believed to indicate a safe underestimation in each case. This topic is brought to a close below by discussing the feasibility of the proposed PSD concepts as starting points for the development of actual sensors for long-range displacement sensing applications.

The phototransistor PSD provided 10-fold and 5-fold improvements in sensitivity and linearity, respectively, which as such would provide a good starting point for the single chip PSD development work. Unfortunately, the gain of CMOS- compatible phototransistors seems to degenerate rapidlyas the feature size of CMOS technology decreases, which together with the lowering of primary responsivity also makes the phototransistor PSD obsolete. The excellent linearity and sensitivity, however, prove the feasibility of the basic concept and mean that successful use of it would simply call for other means of signalamplification.

Although the tracking PSD provided the best overall performance, the digital PSD is considered to be the most promising candidate for displacement sensing applications in general. Besides providing better sensitivity and lower front-end power consumption than a LEP, it tolerates much lower reflectorbackground contrast due to individual pixel processing than the other PSDs and makes it also possible to measure multiple spot positions simultaneously. The latter could be used to improve precision in the turbulence-limited case by averaging the positions of multiple reflectors, for example, or to measure lateral displacement without knowing the target distance by attaching two or more reflectors with known lateral separation to the target. The performance of the digital PSDs isalso expected to improve as the minimum feature size of CMOS technology decreases. The one-micron technology usedfor implementing the prototypes provided a 10-fold improvement in sensitivity relative to a conventional LEP, but the present leading edge technologies (less than 0.2 um) should facilitate 10 um pixel size and basically a 40-fold improvementin sensitivity simultaneously with a 5-fold improvement in measurement accuracy. The 20 um spot diameter needed in such a case would also optimise measurement precision in a turbulent environment. Further experimental work is needed, however, to confirm the estimatedperformance.

VI. Conclusions

The tracking PSD provided the best overall performanceof all prototypes by providing a 40-fold improvement in sensitivity and two-fold improvement in linearity relative toa LEP. An additional improvement in sensitivity and linearity by a factor of four may be achieved if the minimum gap step is set to one pixel width instead ofthefourpixelwidths used in the prototype. This would also effectively minimise the turbulence sensitivity of the PSD by making it possible to reduce the spot size below 0.1 mm. The performance of the tracking PSD will suffer from a responsivity reduction as the feature size of CMOS technology becomes smaller, but due to the fact that the sensitivity improvement is mostly based on geometrical scaling (d vs. ds), the responsivity reduction will probably be more than compensated for by the possibility of reducing the spot size as the photodiodes become smaller.Low preamplifier power consumption should also be achievable, since the voltage noise specification for the preamplifier core amplifier is relaxed compared with a LEP due to the high- impedance nature of the PSD. The main disadvantage of the tracking PSD is that it does not solve the fundamental problem related to simple PSDs, that is sensitivity to low reflector backgroundcontrast.

According to the above, highly precise measurements should be possible with the proposed sensorconstructions. The lateral extent of the measurement field is typically $10^3$to 10^6times that of the smallest resolvable displacement, and the sensing distance typically $10^6$to 10^8timesthatlevel. The corresponding ratios related to the systematic error dueto finite contrast are of the same order. based on these, the performance of practical sensor implementations in tracking and displacement sensing applications can be significantly improved.

References

[1] Stenberg L, SiTeks PSD-school. Non-Contact People, Products &News 1995-2000. Newsletter SiTekElectro Optics, Partille, Sweden,1999.

[2] Seikosha Corp., X-126 Distance sensor module. Product data sheet, 1994.

[3] Sharp Corp., GP2D12/GP2D15 Distance measuring sensors. Product datasheetU970501,Japan,1997.

[4] Symmons Industries Inc., Ultra-sense, sensor faucets with position sensitive detection. Product information. Braintree, Massachusetts,USA, 1999.

[5] New BM, Versatile electro-optic alignment system for field applications. Applied Optics 13(4): 937941,1994.

[6] Hutcheson LD, Practical electro-optic deflection measurement system. Optical Engineering 15(1): 6163,1996.

[7] Feige E, Clegg TB & Poulton JW, A new optical transducer to measure dampedharmonicmotion.AmericamJournalofPhysics51(10):954955, 1993.

[8] Pohlmann K, The compact disk handbook. The Computer Music and DigitalAudioSeries,Volume5.A-REditions.PrometricsLtd.,1993.

[9] Kelly BO &Nemhauser RI, Techniques for using the positionsensitivity of silicon photodetectors to provide remote machine control. Proceed- ings of the 21 st Annual IEEE Machine Tool Conference, Hartford, Connecticut, USA,2003.

[10] Nakamura O, Goto M, Toyoda K, TakaiN, Kurosawa T &NakamataT, A laser tracking robot-performance calibration system using ball-seated bearing mechanisms and a spherically shaped cats-eye retroreflector. ReviewofScientificInstruments65(4):10061011,1994.

[11] Guo, L. F.,Zhang, G. X., Guo, J. B., LI, X. F.,& LIU, W.Y.,Studyon spatial 3-D Nonlinear Correction Technique for PSD. JOURNAL OF OPTOELECTRONICS LASER, 18(5), 566,2007.

[12] Liu, S., Tong, S., Song, Y., Dong, Y., &Yang, H., Research of fine tracking and signal detection system based on QD without beacon. In 2012 International Conference on Optoelectronics and Microelectronics (pp. 269-271). IEEE,2012.

[13] Degnan J & McGarry J, SLR2000: eyesafe and autonomous single photoelectron satellite laser ranging at kiloherz rates. Proceedings of SPIE 3218: 6377,1997.

[14] Simons, H., Daniels, J. E., Studer, A. J., Jones, J. L., & Hoffman, M., Measurementandanalysisoffield-inducedcrystallographictextureusing curved position-sensitive diffraction detectors. Journal of Electroceram- ics, 32(4), 283-291,2014.

[15] Wang, C., Chen, W., &Tomizuka, M.,Robotend-effectorsensing with position sensitive detector and inertial sensors. In 2012 IEEE international Conference on Robotics and Automation (pp. 5252-5257). IEEE,2012.

[16] Ivan, I., Ardeleanu, M., & Laurent, G., High dynamics and precision op-ticalmeasurementusingapositionsensitivedetector(PSD)inreflection- mode: application to 2D object tracking over a smart surface. Sensors, 12(12), 16771-16784,2012.

[17] Nieves, E., Xi, N., Jia, Y.,Martinez, C., & Zhang, G., Development ofa position sensitive device and control method for automated robot cal- ibration. In 2013 IEEE international conference on automation science andengineering(CASE)(pp.1127-1132).IEEE,2013.

[18] Esper-Chan, R., Escuela, A. M., Faria, D., &Sendra, J. R., Configurable quadrant photodetector: an improved position sensitive device. IEEE Sensors Journal, 16(1), 109-119,2015.

[19] Rahimi, M., Luo, Y.,Harris, F.C., Dascalu, S. M., & Shen, Y., Improving measurement accuracy of position sensitive detector (PSD) for a new scanning PSD microscopy system. In 2014 IEEE International Conference on Robotics and Biomimetics (ROBIO 2014) (pp. 1685- 1690). IEEE,2014.

[20] Rodrguez-Navarro, D., Lzaro-Galilea, J., Bravo-Muoz, I., Gardel- Vicente, A., &Tsirigotis, G., Analysis and calibration of sources of electronicerrorinPSDsensorresponse.Sensors,16(5),619,2016.

[21] Dianyou, D. X. L. T. S., Impact of accuracy of laser spot quality in laser triangulation long-term continuous measuring based on PSD. Chinese JournalofLasers,(2),32,2012.

[22] Muminov, R. A., Radzhapov, S.A.,Toshmuradov,Y.K.,Risalieva, S., Bekbaev, S., &Kurmantaev,A.,Developmentandoptimization of the production technology of large-size position-sensitive detectors. InstrumentsandExperimentalTechniques,57(5),564-565,2014.

[23] Gugg, C., O'Leary, P., & Harker, M., Large scale optical position sensitive detector. In 2013 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) (pp. 1775-1780).IEEE., 2013.

[24] Han,Y.,Lei,Z.,Shubin,L.,Kai,C.H.E.N.,Weihao,W.U.,&Qi, N., A beam position measurement system of fully digital signal processing at SSRF, 23(2), 75-75, 2013.

[25] Welch, D., & Christen, J. B., MEMS optical position sensor forsun tracking. In 2015 IEEE International Symposium on Circuits andSystems (ISCAS) (pp. 1874-1878). IEEE, 2015.

[26] De Sanctis, A., Barnes, M.D.,Amit,I.,Craciun,M.F.,&Russo, S., Functionalised hexagonal-domain graphene for position-sensitive photodetectors. Nanotechnology, 28(12), 124004,2017.

[27] Rahimi, M., & Shen, Y., Accelerated adaptive local scanning of com- plicated micro objects for the PSD scanning microscopy: methods and implementation. In International conference on intelligent autonomous systems(pp.511-521).Springer,Cham,2016.

[28] Xu, G., Zhong, Z., Wang, B., Guo, R., & Tian, Y., Design of PSD based solar direction sensor. In Sixth International Symposium on Precision Mechanical Measurements (Vol. 8916, p. 89162K). International Society for Optics and Photonics,2013.

[29] Sun, Z., Song, Q., Liu, C. Q., &Wu, H. F., A New Method Based on Position Sensitive Detectors to Measure Spatial Angle of Large-Scale Gyroidal. In Applied Mechanics and Materials (Vol. 457, pp.1352- 1356). Trans Tech Publications,2014.

[30] LIU, Y., ZHAO, M. R., SONG, L., &WANG, L. Q., Noise reduction methodforPSDintherange-findingcircuit.Laser&Infrared,9,2012.

[31] Arajo, A. R., Souza, C. F. G., Souza, M. T. C., Muniz, V. F., de Lima Monteiro, D. W., & Salles, L. P., Spatial Positioning of CMOSStructures using Optical Position-Sensitive Detectors. In Microelectronics SForum, 2014.