DESIGN AND DEVELOPMENT OF A LINEAR VARIABLE DIFFERENTIAL OPTICAL SENSOR FOR SMALL RANGE LINEAR DISPLACEMENT MEASUREMENT

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Abstract

In this present paper, we have illustrated the development of a novel linear displacement sensor utilizing the intensity of light. This sensor is based on temporal changes in the intensity of diffuse light beam for the movement of a solid metallic obstacle between the source and detector instead of traditional reflector. An obstacle is moved over open surface of a hollow shaped channel, where light beams impinged vertically into the channel. Two photo detectors has been used to sense the variation of diffuse light intensity at the covered & uncovered area of channel surface due to the movement of obstacle over its open surface. This movement of an obstacle represents the actual target displacement by differentiating the output transformation of two photo detectors; this phenomenon is reported as linear variable differential optical sensor (LVDOS). The measured displacement recorded interns of voltage by the signal processing circuit (SPC). Experimental results are shown a satisfactory performance of the sensor for small range displacement measurement.

Index terms: *Linear Variable Displacement Sensor, Intensity of diffuse light beam, solid metallic obstacle, Photo detector*

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1. INTRODUCTION

In modern industrial production processes the actual linear or angular displacement of fast moving objects needs to be detected and ideally done with or without mechanical contact [1]. For this, there exist variety of suitable sensors that provide an output signal (voltage or current) proportional to the displacement of target and sensor. In industrial usage there are exactly defined requirement for reliability, ruggedness, measuring range etc [2]. Likewise, electrical parameters such as supply voltage range, output signal and EMC requirements are firmly defined in norms and standard [3]. Also the displacement sensor used in various field of sensitive & accurate systems such as a robot, biomedical measuring device, rectilinear motor, controlling of servomotor piston bump and so on. To find the best sensor for the displacement purpose, the accuracy factor is very important to be considered.

In this present work we have focused on small range of linear displacement sensing methods. Various researchers have developed varieties of linear displacement transducer in aspect of range of displacement, sensitivity, linearity and accuracy. Like Linear variable differential transformer (LVDT) [4], capacitive transducer [5], potentiometeric transducer [6], resistive transducer [7], etc. Each of these transducers has its drawbacks and imperfections.

The drawback of LVDT is that it has larger body length, affected by magnetic field and complicated signal conditioning circuit. All of these tribulations are trying to rectified by Dhiman et.al [8], implementing a strain gauge based displacement sensor & A.K.Alia et.al [9], implementing an Acoustic Displacement Transducer, which is suffering from the environmental noise and self oscillating detector by means of reflected sound energy. On other side strain gauge based displacement sensor introduced mechanical error in terms of ruggedness.

Where linear displacement measured in the range of millimeter or less by applying very small force, capacitive displacement sensors are useful for that operation. They have a good frequency response but its nonlinearity behavior on account of edge effects and high output impedance on account of their small capacitance value; add to this, that the cable which connects the transducer to measuring point is a source of error. Moreover, the capacitance may be changed because of the presence of dust particles and moisture or because of temperature change.

Potentiometric or resistive transducer operating range is limited by the size of potentiometer and it is also affected by the friction caused to obstruct the slider movement. Although it is quite useful in some applications they have noticeable friction and need physical coupling with the object. Wiper friction and excitation voltage cause heating of potentiometer.

Optical sensors have advantages over other type of sensors in that they can provide noncontact operation, greater sensitivity, and better accuracy, freedom from electromagnetic interference, wide frequency, and dynamic ranges. From these advantages, optical techniques may be ideal for the development of sensors for the measurement of small linear displacement.

Optical incremental and absolute digital encoders are the most common rotational position optical transducers. Absolute encoders overcome some disadvantages of incremental type, but are more expensive. Generally optical encoders find use in relatively low reliability and low resolution applications [10]. Both types may suffer damage in harsh industrial environment [11]. For sensing the linear displacement, linear encoder and quadrature encoder are traditionally used. Historically, the practical disadvantage of optical encoders have included pattern inaccuracies, concentricity errors between disc and shaft, susceptibility to electrical noise, vulnerability to shock and lose of data in power failure. One of major problems with optical encoders; ice crystal formation and resultant pattern damage when the shaft turns has not really been completely solved. Instead of optical encoder some of the researchers work on the principle of variation of light intensity due to reflection of optical signal from the target or measuring shaft which is the source of displacement. Maiti.et.al [12] & Mhdi.et.al [13] developed a linear variable differential displacement sensor based on optical light intensity variation method. The drawbacks in such systems are the reflected light could not attain the same incident angle and reflection angle between the source and detector after variation from steady state position of the reflector, it was scattered from the detector. So the expected variation of light intensity due to the displacement makes an error. To overcome this problem S. J. Lee.et.al [14] designed a Magneto-optic linear-displacement sensor which is based on modulation of Faraday rotation due to domain-wall motion in a magneto-optic sensor film under the influence of ac and dc magnetic fields. It is largely independent of the intensity of reflected light but its displacement measurement process depends of time interval. So this type of sensing arrangement is not suitable for fast moving object displacement measurement. Without use of traditional reflector and time independent sensor designed has been proposed by S. Das and T.s.Sarkar [15] which introduced better accuracy, linearity and sensitivity within a small space range of 0 to 40mm.

In this present paper we have introduced a new Linear Variable Differential Optical Sensor (LVDOS) which is independent of time and conventional reflection scheme. It is suitable for fast moving object and as well as measurement of small linear displacement. The prototype sensor module works on the principle of light intensity variation method by establishment of an obstacle between the source and detector instead of reflector, which is the source of displacement. To sense the light intensity, a photo detector has been placed horizontally at the ground surface plane of a one sided open hollow channel. The open sided surface allows the incident light beams vertically from the source and a solid piece of obstruction was moved horizontally over the open sided surface, initially which are kept at centre position of the channel surface. In this connection, photo detectors illuminated by the reflected light rays by the side walls of the channel. As the solid metallic piece moves towards the end position of the channel from the centre due to the displacement of the target with the attachment of this, the open sided surface being covered. Hence the ratio of covered area and uncovered area of that surface changed accordingly. Due to this phenomenon photo detector detects the variation of reflected light intensity according to the rate of changes impinging light incidents. The photo detector outputs recorded in terms of voltage and difference between the intensity level of covered and uncovered area exhibits the direction of displacement & the magnitude of displacement. It is employed by a signal processing circuit (SPC). We proved successfully that this system works as a small linear-displacement sensor. The introduction is followed by a representation of the LVDOS working principle, constructional details, the experimental investigation, and a series of discussion topics based on experiments.

2. PHYSICAL BACKGROUND

As the light incident on the surface, it is reflected in all direction due to internal scattering of light (i.e. the light is absorbed and then re-emitted) and external scattering from the rough surface of the object. This is called the diffuse reflection as shown in the Fig.1

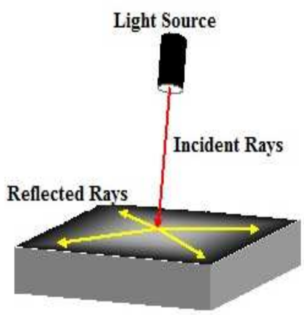

Fig-1: Diffuse reflection in all directions

From fig.1 it is obvious that if a point of light source kept perpendicularly over the surface then incident light rays are not parallel like diameter of light source, it diverges at an angel which is described by the Gaussian beam functions. If a light beam of wavelength λ falls perpendicularly on a surface, then it will be diverged at an angel of θ which is developed between the incident light rays and the central axis of light beam; expressed as

$$\theta \approx \frac{\lambda}{\pi w_0} \quad (\theta \text{ in radians})$$

Where, w0 is the radius of the spot near the source point. The Gaussian beam functions of different diameter of light source are shown in Fig.2.

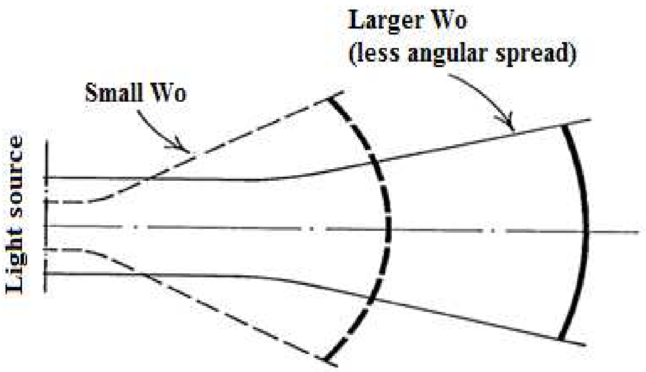

Fig-2: The Gaussian beam divergence for different kind of source point

From Fig.2 it is concluded that the point of light source spreads largely on a surface rather than the others light source. So, illuminating the more area by keeping a smallest distance between source and object, a point of light source is very useful.

The brightness or intensity of any point in the surface where the light incidents, is depended only on how much light is reflected or diffused from the surface. It can be calculated by Lamberts cosine law which states that the intensity of diffuse light rays depends on the cosine angle between the normal at that point of the surface and the light source illuminating on it. It is expressed as

$$I = Ip \,.\, Kd \,.\, \cos\theta$$

Where, Ip is the intensity of point light source and Kd is the material's diffuse reflection coefficient; expressed between 0 and 1 which depending on material to material. Fig.3. shows the diffuse lighting on the surface with different angles between any points of a surface (i.e. normal on that point) and the incidents light rays.

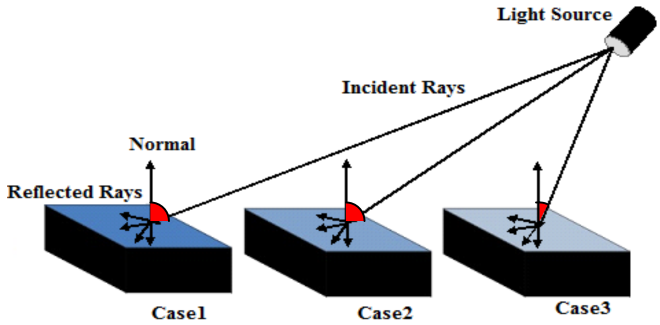

Fig-3: Diffuse light intensity at different angels

From Fig.3 we observed three cases of diffuse reflection on the surface such as-

Case 1: The angle between the normal and the incident light rays is large, so little light is reflected from the surface. Case 2: More light is reflected than case 1 as the angle is reduced between the normal and the incident light rays. Case 3: A large amount of light is reflected from the surface when the angle between the normal and the incident light rays tends to zero.

So it is concluded that most of the light is reflected when the angle is at 0 degree, none is reflected at 90 degree due to cosine angel between the normal and the incident light rays. For measuring the light intensity level if a photo detector has been placed in case1 surface, it is observed that the detected light intensity level at that surface has been varied due to blocking the incident light rays by placing a non transparent obstacle in light travelling path. Because no light incident or reflected on that point directly and very small amount of reflected light reached at that point from the nearest case2 surface. If this obstacle moved on serially from case1 to case2 and then case3 and so on then photo detector output changed accordingly from smallest value to larger value; means case1 surface moves to much more darkness level. This phenomenon has been employed in our proposed LVDOS system.

3. DESIGN OF LVDOS

In this present design, light source part & light receiving part separated by a metallic obstacle. The receiving parts consist of a light reflective container and two photo detectors. A one sided open hollow shape aluminum channel is used as a light reflective container instead of glass, which is commonly used as a light reflective surface. From industrial aspect of ruggedness glass is poor compared to any metal. Some metallic surface oxidized naturally with the contact of air and made surface layer less reflective whereas aluminum does not exhibit this property. In this connection our prototype sensor’s channel surface made with aluminum. The length of the channel is 12 cm, height 1 cm, width 2.5 cm.

At the centre position of the channel, two photo detectors were placed back to back on a very thin insulated plate which is separated the channel into two parts, each of having 6 cm lengths. From the top view of the channel as shown in Fig.4, it is observed that the width of the open sided surface is 1.5 cm instead of 2.5 cm due to 0.5 cm (width) inner bending surface of the two side walls of the channel. The purpose of that bending surface is an obstacle of 6 cm long, 3 cm wide & 0.5 cm height cubic metal plate can moves over the open sided surface horizontally with the displacement of the target body by making an attachment of shaft at the both end of the obstacle. The shaft designed & connected in such a way that it could not behaves as an obstacle, so it is free from addition a permanent error in intensity variation due to the original movement of obstacle.

The light source part separated in two modules, each of length is 3 cm. Each module is made with 8 no. of LEDs. Because one LED is not enough to lighting up the whole length of a channel part by keeping it small distance apart from the surface as the statement of Gaussian divergence angel relation, which is stated in physical background. Each module driven by an array of current limiting resistors in series with +5 V regulated power supply. The side view of the arrangement is shown in Fig.5.

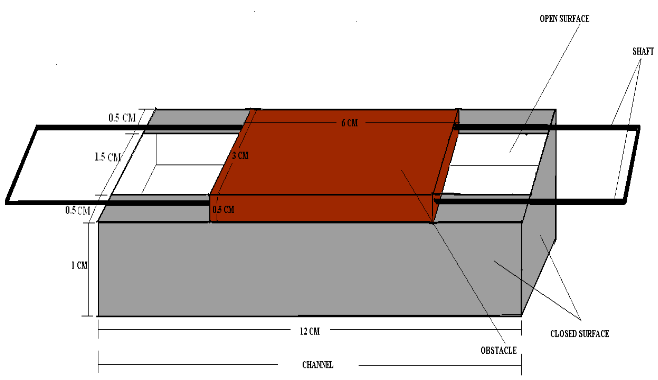

Fig-4: Top View of the Channel with Obstacle

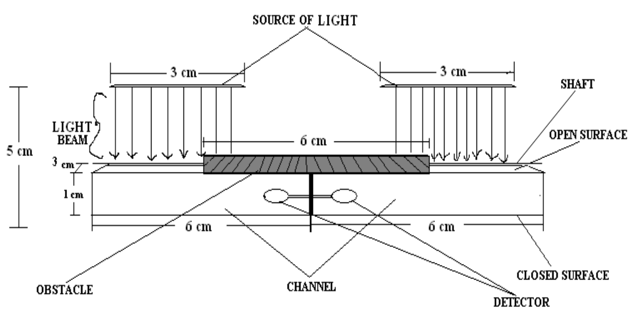

Fig.5. Side View of LVDOS

4. WORKING PRINCIPLE OF LVDOS

At the initial position, obstacle is kept at the centre position over the open surface of the channel i.e. half part of an obstacle covered right portion & other half part of an obstacle covered left portion of the channel. The two photo detector has been placed just under the obstacle at that position as shown in Fig.5. The light beam from the sources is impinged vertically through the open surface of the channel where obstacle is not present. As a result two photo detector sense some diffused light intensity due to light reflection policy. Now, if we move the obstacle towards right from the centre position of the channel by a distance of 1 mm using a vernier scale arrangement, the open surface of the right portion has been covered and left portion has been uncovered by similar distance. In this connection the initial detected light intensity level of a right photo detector (RPD) is dropped due to obstruction of incident light rays and left photo detector (LPD) detected intensity level increased due to much more incident light reflection as stated in physical background. This movement of the obstacle is continued until it reached to extreme right position of the channel and detected light intensity level of RPD drops gradually towards zero i.e. right portion of the channel is fully covered by obstacle and detected light intensity level of LPD increase gradually towards saturation point i.e. left portion of the channel is fully uncovered. This same incident would be happened for obstacle movement towards left side, but the detected light intensity level variation of two photo detectors will be changed in reverse order. The schematic diagram of complete sensor module is shown in Fig.6.

To sense the light intensity variation we used two photo diodes as detector. In reverse bias configuration of photo diode, current will be changed in the circuitry according to the light intensity level, which converted into voltage variation by an op-amp based current to voltage converter circuit. Further these two voltages of photo detectors are differentiate by a signal processing circuit (SPC) & final output voltage (Vo) is recorded with the displacement of the obstacle in the range of +3cm to -3cm i.e. from centre position to extreme left and centre position to extreme right position. Thus, measuring the output voltage (V0) of the SPC, we can detect the linear differential displacement/position of the obstacle.

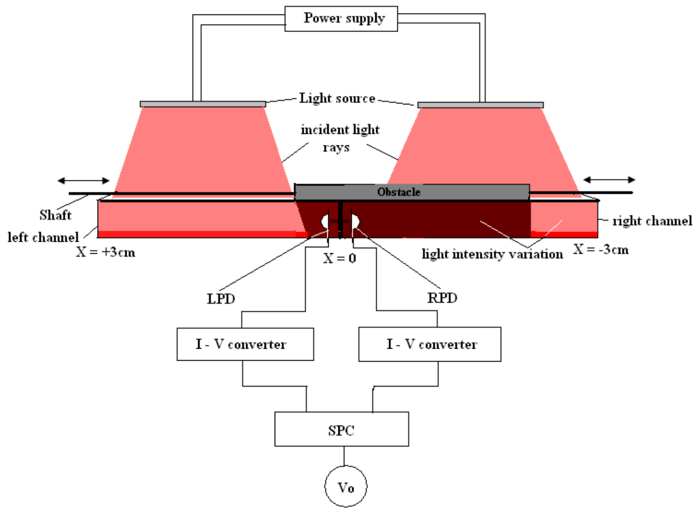

Fig-6: Schematic diagram of complete sensor system

5. RESULT ANALYSIS

The polynomial output voltage vs. displacement relationship of two photo detectors are obtained with the help of MATLAB curve fitting tools (considering up to 4th order only) , shown in Fig.7 and can be written as

V_{01} (D) = - 0.006 D4 + 0.024 D3 + 0.076 D2 – 0.596 D + 0.980 (1)

Where V_{01} (D) is the output voltage of RPD for a movement of obstacle with the displacement of D cm and

V_{02} (D) = -0.007 D4 - 0.024 D3 + 0.080 D2 + 0.597 D + 0.986 (2)

Where V_{02} (D) is the output voltage of LPD for a movement of obstacle with the displacement of D cm similarly, the polynomial relationship between the output voltage (V_0) of the SPC and the displacement of obstacle D is obtained by the curve fitting tools (shown in Fig.8) using MATLAB and this is expressed as

V_0 (D) = P4 D4 + P3 D3 + P2 D2 + P1 D + P0 (3)

Where the above coefficient is calculated by the difference of coefficient, which is provided in equations (1) & (2) Because, the output voltage (V0) is the difference of two photo detector output voltages V01 & V02. Therefore,

V0 = V01 – V02 (4)

So, polynomial coefficient of equation (3) is

P4 = 0.001 P3 = 0.048 P2 = -0.004
P1 = -1.193 P0 = -0.006

When the obstacle moves towards negative direction i.e. towards the extreme right position of the channel, the darkness level at the right channel will be increase rather than the darkness level at the left channel. Hence, the output voltage of the RPD (V_{01}) will be smaller than the output voltage of the LPD (V_{02}). So the differential output voltage of the SPC (V_0) is (-) ve. Similarly, when the obstacle moves towards positive direction i.e. towards the extreme left position of the channel, the darkness level at the left channel will be increase rather than the darkness level at the right channel. Hence, the output voltage of the LPD (V_{02}) will be smaller than the output voltage of the RPD (V_{01}) and the differential output voltage of the SPC (V_0) would be (+) ve. Thus, this technique provides theoretically non-linear relationship between the differential output voltage and linear displacement.

It is obvious from equations (1), (2) & (3) that when the obstacle is in middle position i.e. when D = 0, all the output voltages of two photo detectors and SPC are providing the non-zero value i.e.V01 (0) ≠ 0, V02 (0) ≠ 0 and V0 (0) ≠ 0. By acquiring the experimental data of two photo detector output voltage (V01 & V02) and output voltage (V0) of SPC for linear displacement (D) of an obstacle has been graphically plotted in Figure 7 & 8 which supports the equations (1), (2) & (3). The enlarge view of linear region of SPC output voltage (V0) vs. linear displacement (D) curve has been shown in Fig.9.

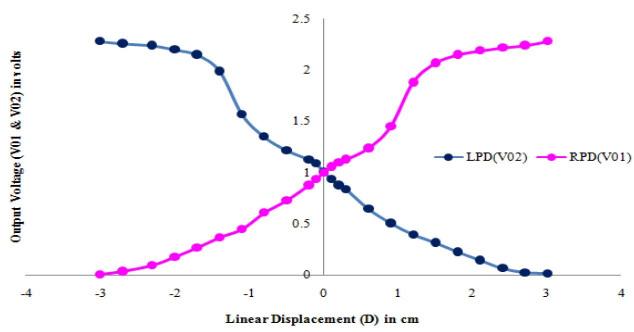

Fig-7: Plot of output voltages of two photo detectors against linear displacement of an obstacle

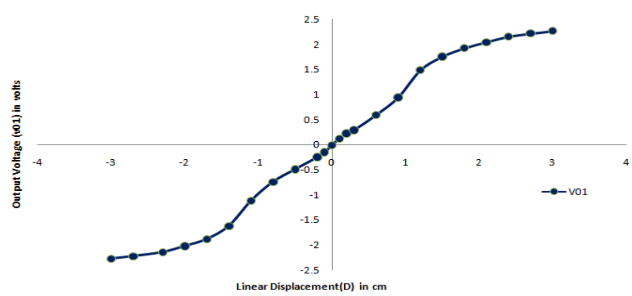

Fig-8: Plot of output voltage (V_0) of SPC vs. linear dispalcement

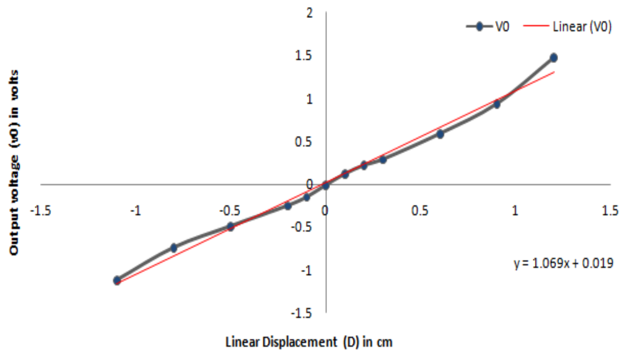

Fig-9: Enlarge view of linear range of output voltage (V_0) of SPC vs. linear dispalcement

The experimental result shows a linear variation of output voltages with the variation of linear displacement in the range of +1cm to -1cm instead of +0.5cm to -0.5cm displacement range of a linear variable differential displacement sensor [12]. Eventually we have calculated the non linearity of that curve utilizing best-fit straight line method and find the value of -6.15% FSO (Full Scale Output) at the displacement of -8mm. Also the accuracy factor of that measurement method is -2% FSO at 4mm.

The proposed sensing method can measure the smallest displacement of 1mm i.e; resolution of this method is 1mm. So it exhibits better resolution than optical LVDT [12] and Acoustic displacement transducer [9] which shown 10mm and 5mm respectively.

The repeatability of that sensing method has been evaluated as 0.04%FSO.

CONCLUSIONS

By utilizing the variation of light intensity of a LVDOS was designed and tested successfully.

The designed sensor is efficient, in expensive, and multipurpose. It could be integrated with other primary non electrical sensors and order to get an electrical read out.

This LVDOS displacement sensor applicable in various industrial fields such as robot, biomedical measuring device, rectilinear motor & position feed back of a pneumatic or hydraulic cylinder rod. In this case the sensor is not embedded within the target, but externally tied through a yoke to the target body

From Fig.9 the output voltage (V0) variation with target displacement has been observed linear in the range of -1cm to +1cm. But beyond this range curve shows non linearity in both -ve & +ve range. So accurate measure of displacement in present & extended range, computer or embedded based programming can be used by interfacing this sensor with the DAS card & PC, it is the future scope of work.

REFERENCE

[1] Villaverde, A. B. , Munin, E. and Pedroso, C. B. (1998), Linear Displacement Sensor Based on the Magneto-optical Faraday Effect, Sensors and Actuators A 70, pp 211 – 218.
[2] Gang Zhang, Youping Chen, Zude Zhou and Shaouhui Li. 2006. Design of an Inductive Long Displacement Measurement Instrument, Proceeding of the 6th World Congress on Intelligent Control and Automation, June 21-23, Dalian, China, Page(s): 5098-5101.
[3] H.Wakiwaka, S.Yanase and M.Nashizawa. 1996. IEEE, Characteristics of Meander Coil Impedance with OpenedScale Coil for Linear Sensor, Page(s): 487-492
[4] Saxena, S.C. and Saksena,S.B.L., A self compensated smart LVDT transducer, IEEE Trans. Inst.& Meas. Vol. 38 No. 3, 1989, pp. 748-753.
[5] Toth, F. N., and Meijer, G.C.M., A low cost smart capacitive position sensor, IEEE Trans. Inst.
& Meas. Vol. 41 No. 6, June 1992, pp. 1041-1044.
[6] David and S. Nyce, Linear Position sensors, theory and application, Wiley Inter Science, UK, 2004.
[7] X. Li and G. C.M. Meijer, A novel smart resistive-capacitive position sensor, IEEE Trans. Instrum. Meas., 44, 1995, pp. 768-770.
[8] Pradeep Kumar Dhima1, Kirat Pal and R. K. Sharma, “Strain Gauge Based Displacement Sensor”, Journal of Physical Sciences, Vol. 10, 2006, pp-164 – 166
[9] Tariq Al Mograbi, Mohammad A. K. Alia, Mohammad Abuzalata, “Design of an Acoustic Displacement Transducer”, Sensors & Transducers Journal, Vol. 112, Issue 1, January 2010, pp. 1-9.
[10] Johns Wilson, Sensor technology Handbook, News, UK, 2005.
[11] John A, Allocca, Allen Stuart, Transducer, Theory and applications, Reston Publishing Company, Inc.,Virginia, USA, 1984.
[12] Tapan Kumar MAITI, Prasenjit PAUL, Indrajit DAS and Soumen SAHA “PC Based Linear Variable Differential Displacement Measurement Uses Optical Technique” Sensors & Transducers Journal, Vol.81, Issue 7, July 2007, pp. 1341-1347
[13] Bushra R. Mhdi, Nahla A. Aljaber, Suad M. Aljwas, Abeer H. Khalid, “Design and Construction of Optical Fiber Sensor System for Detection of the Stress and Fine Motion” International Journal of Nano Devices, Sensors and Systems (IJ-Nano) Volume 1, No. 1, May 2012, pp. 25-33
[14] S. J. Lee,a_ Y. Melikhov, D. C. Jiles, C. M. Park and H. Hauser “Magneto-optic linear-displacement sensor with high spatial resolution and low noise” journal of applied physics 99, 08B301 _2006.
[15] S. Das, T. S. Sarkar, “A new method of linear displacement measurement utilizing a grayscale image”,

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BIOGRAPHIES

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