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Improving of Characteristics of Rotary Angular Sensor Using Nonlinear Transparent Disc

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Abstract: As the angular position sensor is a main sensor to measure an accurate position and direction, it plays an important role in various applications such as robotic controller, camera and industrial machines. Recently, lots of angular position sensors such as simple resistive potentiometer, capacitive potentiometer, optical sensor and magnetic sensor are described in several literatures. This paper has described a simple absolute rotary angular sensor with a nonlinear transparent disc. This sensor consists of five elements such as light-source, a shaft coupled nonlinear transparent optical disc, lens, a pair of light dependent resistor (LDR) and a signal processing circuit. This absolute rotary angular sensor is one of non-contact potentiometer based on characteristic of resistance via irradiance and has an advantage to fabricate easily as disc is made with fiber glass and a self-adhesive tape of which transparency is nonlinearly changed in a range of 0-360°. Also this sensor has a good linearity of R^2 = 0.99999, a good repeatability of maximum characteristic drift around ±0.1° and measurement error below ±0.5°. And measurement stability is ±0.1° within its full operating range from 0° to 360°. The proposed disc assembly and overall results can be helpful to design absolute rotary angular sensor for performance improvement of it. It seems that the proposed method has important practical significance for the development of optical absolute rotary angular sensor.

Keywords: Potentiometer, Rotary Angular Sensor, Transparency, Brightness, Encoder

1. Introduction

As the angular position sensor is a main sensor to measure an accurate position and direction, it plays an important role in various applications such as robotic controller, camera and industrial machines [1–4].

Recently, lots of angular position sensors such as simple resistive potentiometer [5], capacitive potentiometer [6], optical sensor [7] and magnetic sensor [8-10] are described in several literatures.

Generally, rotary angular sensor can be classifi according to the physical principle used for the measurement, namely sensors based on changes in the electric field, the magnetic field and the optical sensor. There are two kinds of Electric-field-based sensors such as resistive [5] and capacitive types [6]. The advantage of the resistive potentiometer is a simple structure but there is a disadvantage to need the physical contact between the stator and the rotor, causing mechanical wear and contact noise. And also, the resistive potentiometers always lead to abrasion and instability owing to the physical coupling between stator and rotor [11].

Capacitive potentiometer has a disadvantage to change the sensitivity by external electric fields, contamination and variations in the space between the electrodes [12, 13].

Magnetic-field-based sensors can be divided into magneto-astrictive sensor [8, 14], magneto-resistive sensor [10] and Hall-effect sensor [11].

These sensors' disadvantages are to need complex and special structures to avoid the external magnetic field effect [15, 16].

But optical sensors which operate on visible light or infrared light offer the advantages of a contactless measurement and insensitivity to electric and magnetic fields [11].

Although these optical sensors' sensitivity is decreased by background light, this problem may solve easily by the packaging and using pulsed light. So an optical angular sensor has become recognized as an indispensable displacement/position sensor due to its high resolution, light weight and excellent immunity to electromagnetic interface.

Generally, an optical angular sensor consists of a code scale, an optical sensing head and a signal processing circuit. Also, an optical angular sensor can be classified as reflection and transmission type according to the placement of code scale and sensing head in its housing.

In these sensors, the lights passed through the coded scale and information is retrieved by photo-detector [17]. As result, photo-detector receives high/low intensity of lights after passing through transparent and semi-transparent micro slits of the disc. So signal processing unit identifies the logical high/low bits of the code as a function of light intensity [23, 24].

But it is difficult to make this type angular sensor due to use of lithographic method to design these micro slits in glass plate. And also this type angular sensor has a critical fault to maintain a gap between code disc and detectors for reliable operation.

In order to solve this fault, a new optical angular sensor with a low cost disc is proposed. [17]. This type disc is based on simple grayscale transformation of RGB colored hue wheel and decoder unit consists of three optical reflection type color sensors. This design claimed an accuracy of ±1° and resolution of 0.1° within the range of 0–360°.

The new type of absolute rotary angular sensor to have the disc covered up by a semi-transparent self-adhesive tape except the circumference edge of a quadrant is proposed [18].

In this paper, we have described an absolute rotary angular sensor with nonlinear transparent disc and a pair of light dependent resistor (LDR). This rotary angular sensor is a transparent type sensor and has a nonlinear transparent disc between light source and LDRs. This sensor consists of five elements such as light-source, a shaft coupled nonlinear transparent disc, lens, a pair of light dependent resistor (LDR) and a signal processing circuit. In this sensor, absolute rotary angle is measured by output resistance of double LDRs which has a linear change by nonlinear transparency of disc in a range of 0-360° according to characteristic of LDR's resistance via irradiance.

This sensor's operation principle is similar to the resistive potentiometer. The signal processing circuit which consists of 24bit AD converter ADS1252 and microprocessor STM32F103RB converts the output signal of LDRs into digital signal such as SPI protocol.

This sensor's advantage is to have nonlinear transparent disc instead of binary coded disc and too large gap distance between of disc and optical sensor hence it is immune to shock and vibration. As result, sensor can be easily fabricated. The disc is made with fiber glass and covered up by a self-adhesive tape of which transparency is nonlinearly changed in a range of 0-360°.

Another advantage of this sensor is to be determined its resolution by AD converter in signal processing circuit as output signal of LDRs is analogue signal. Therefore, this rotary angular sensor is provided a high resolution in a range of 0-360°.

Sensor proposed in this work has a good linearity of R^2=0.99999, a good repeatability of maximum characteristic drift around ±0.1°, measurement error below ±0.5° and measurement stability is ±0.1° within its full operating range from 0° to 360°

2. Principle of Operation and Implementation of Disc

2.1. Principle of Operation

Absolute rotary angular sensor proposed in this paper is a new type of noncontact potentiometer with a pair of light dependent resistor (LDR) and nonlinear transparent disc. Figure 1 shows operation principle of absolute rotary angular sensor presented in this paper. Generally, output resistance of LDR is dependent to irradiance of incident light [19, 20]. Therefore, rotary angle of shaft can measure by change of output resistance if irradiance of incident light changes according to rotary angle of shaft as shown in shown Figure 1. By the way, as output resistance of LDR has a nonlinear relationship to irradiance of incident light, rotary angle can analogically measure by resistance in terminal T_2 if irradiance of incident light is changed to keep linear change and constant sum of output resistances in LDR_1 and LDR_2 during rotation of shaft.

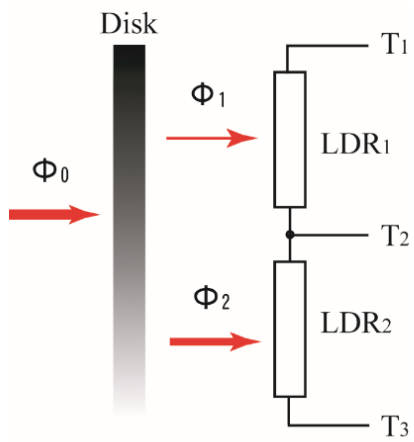


Figure 1. *Equivalent circuit.*

In other words, if irradiance of incident light in LDR is changed according to the LDR's characteristics of resistance via irradiance, output resistance of LDR will be changed linearly. From this, it is very important to fabricate a new nonlinear transparent disc to realize an irradiance adjustment of incident light in LDR according to LDR's characteristics. To do this, it is necessary to adjust transparency of disc according to LDR's characteristics in condition of a constant irradiance of light source.

Generally, LDR's characteristic of resistor via irradiance is as follow [20]

$$R = m \cdot \Phi^{-\beta} \tag{1}$$

where R: resistance of LDR.

Φ: irradiance of incident light.

β: constant.

And also, resistance of LDR has to change linearly according to rotary angle of shaft in the a range of 0-360^0, namely

$$R = k \cdot \varphi + R_0 \tag{2}$$

where k: coefficient,

ψ: rotation angle,

R_0: resistant when brightness of disc is 100%.

From this, resistance will be changed linearly if irradiance of incident light changes as eq. (3).

$$\Phi = \exp\left[-\frac{\ln\left(\frac{k \cdot \varphi + R_0}{m}\right)}{\beta}\right] \tag{3}$$

2.2. Implementation of Disc

It is not easy to realize above-mentioned method. Furthermore, printing a disc which transparency is varied nonlinearly according to exact rotary angle is very difficult task. So in order to solve this problem, we have used HSB color space. HSB color space is a color space in which hue H, saturation S and brightness B are used as coordinate axes and brightness B corresponds to the relative brightness in the sense of a gray-level image [21]. Therefore if only brightness B is varied in condition of constant value of hue H and saturation S, transparency of disc will be changed. In other words, if brightness B is changed from 0% to 100% in condition of H=0 and S=0, color will be changed from black to white and image colors will be converted into gray-level colors. So if grayscale image is printed on disc, transparency of disc will be changed according to rotary angle of shaft. By the way, it is important to measure a relationship between brightness B and output resistance of LDR as output resistance of LDR has a nonlinear relationship to intensity of incident light.

From this reason, we have divided the brightness of image into 20 sections and printed on disc in order to measure a relationship between brightness of image and output resistance of LDR. Figure 2 shows the disc when brightness of image is 50%. And Figure 3 shows Interface of Adobe Photoshop software which use in change of image brightness to make several discs with different transparency.

GaAlAs infrared light emitting diode TLDR5400 (Peak wavelength: 650nm, max Luminous intensity: 70mcd) [22] is used as the light source in this measurement. And max anode current (20mA) flows through LED to know a max range of output resistance change of LDR. Digital Tester DT830B is used as ohmmeter. Figure 4 shows the experimental setup to measure a relationship between brightness of image and output resistance of LDR.

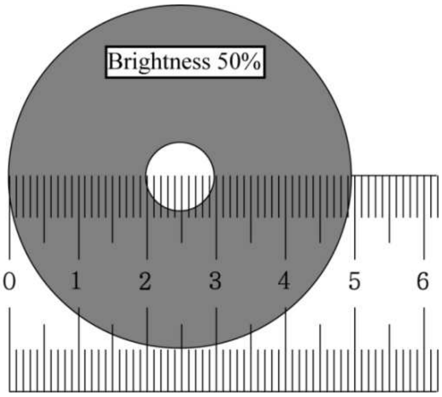


Figure 2. *Disc when brightness of image is 50%.*

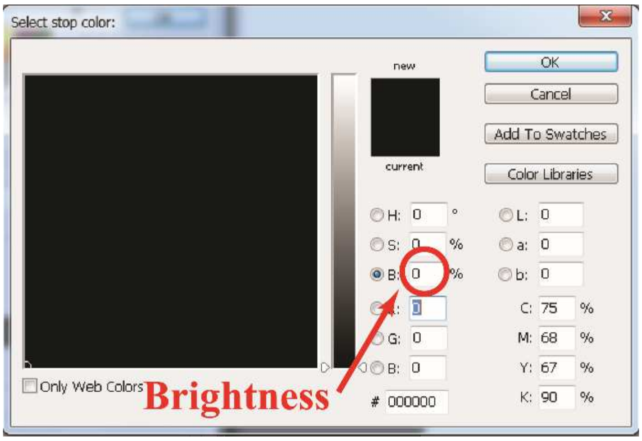


Figure 3. *Interface of Adobe Photoshop.*

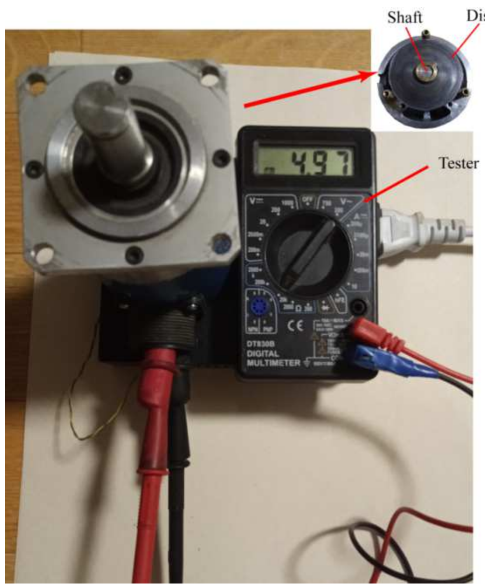


Figure 4. *Experimental Setup to measure a relationship between brightness of image and output resistance of LDR.*

Table 1 shows the experimental results between brightness of image and output resistance of LDR.

As known in Table 1, output resistance of LDR decreases nonlinearly while brightness of image increases linearly. And nonlinearity of LDR's output resistance is decreased when brightness of image is higher than 20%. Approximate function (like type of eq. 1) has been calculated from measurement data of Table 1 by MATLAB application software in condition that brightness of image is higher than 20%. (m=142.3, β=-0.8581). Only measurement data in range of 20-100% is used to calculate the approximate function as nonlinearity. Comparing the calculated results in approximate function with measurement data, adjusted R-square statistics R^2 =1.000, sum of square due to error SSE=4.866×10^{-6} and root mean square error RMSE= 0.0005696. This shows that the approximate function has a good fitness to measurement data.

Table 1. *Experimental results between brightness of image and output resistance of LDR.*

Brightness, %	Resistance of LDR, kΩ	Brightness, %	Resistance of LDR, kΩ
0	755.7	55	4.57
5	35.75	60	4.24
10	19.72	65	3.96
15	13.92	70	3.71
20	10.87	75	3.50
25	8.98	80	3.31
30	7.68	85	3.14
35	6.73	90	2.99
40	6.00	95	2.86
45	5.42	100	2.74
50	4.97		

Brightness of image during shaft rotation in a range of 0-360° has been calculated from eq. 3 in k= 0.02261147 and R_0=2.735kΩ.

Also output resistance of LDR has been calculated in corresponding brightness of image respectively.

Table 2 and Figure 5 show the calculated results.

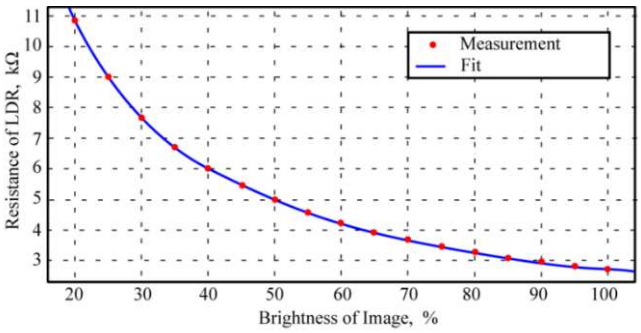


Figure 5. *Calculated result in approximate function.*

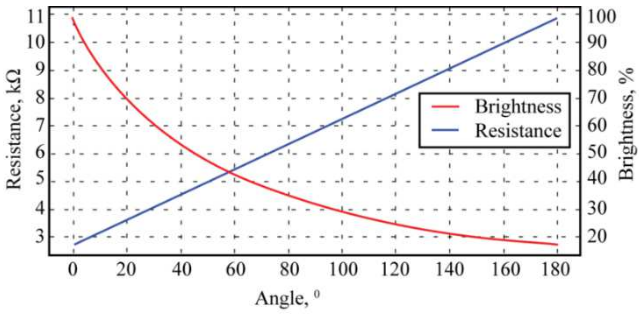


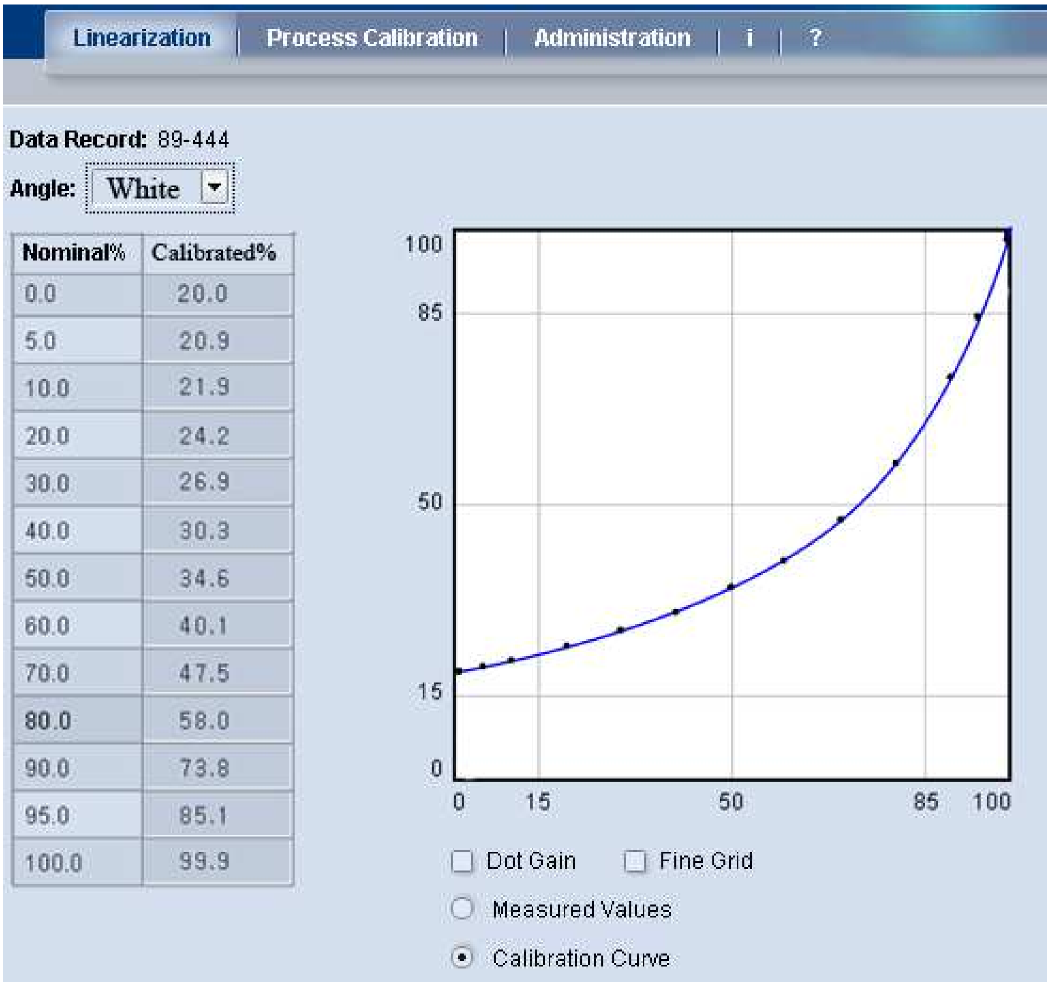
Figure 6. *Relationship of brightness and output resistance of LDR via rotary angle.*

As known in Figure 6, brightness of image decreases nonlinearly and output resistance of LDR increases linearly as increasing rotary angle of shaft in a range of 0-360°. This shows absolute rotary angular sensor which is similar to noncontact potentiometer can be manufactured by disc which nonlinear brightness of image printed on and a pair of LDR.

Table 2. *Calculated result of brightness of image and LDR's resistance.*

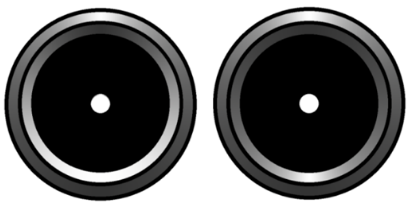
Angle, °	Brightness,%	Output Resistance of LDR, kΩ	Angle, °	Brightness,%	Output Resistance of LDR, kΩ
0	99.97502	2.735886	95	33.27433	7.032065
5	91.13839	2.962001	100	32.06945	7.25818
10	83.65064	3.188115	105	30.9432	7.484295
15	77.2306	3.41423	110	29.88829	7.710409
20	71.66949	3.640345	115	28.8983	7.936524
25	66.8091	3.86646	120	27.96756	8.162639
30	62.52746	4.092574	125	27.09102	8.388754
35	58.72909	4.318689	130	26.26419	8.614868
40	55.3382	4.544804	135	25.48305	8.840983
45	52.29391	4.770918	140	24.74401	9.067098
50	49.54677	4.997033	145	24.04382	9.293212
55	47.05621	5.223148	150	23.37957	9.519327
60	44.78864	5.449262	155	22.74863	9.745442
65	42.71605	5.675377	160	22.14862	9.971556
70	40.81485	5.901492	165	21.57736	10.19767
75	39.06509	6.127607	170	21.03288	10.42379
80	37.44977	6.353721	175	20.51339	10.6499
85	35.9543	6.579836	180	20.01725	10.87602
90	34.56612	6.805951			

In order to manufacture the disc which nonlinear brightness of image printed on, film printer PRIMSETTER-102 has used. Film printer PRIMSETTER-102 on basis of laser lithographical technology is the automated printing machine from preparation of computer data to printing. So there is the calibration function of brightness in driver software of this printing machine. This paper has used this calibration function of brightness to change the transparency of disc nonlinearly according to rotary angle of shaft, namely, to have the nonlinear brightness of image as shown Table 2. Figure 7 shows interface of brightness calibration software. The linear transparent disc is converted to nonlinear transparent disc by interface of brightness calibration software in PRIMSETTER-102 driver software. Figure 8 shows a disc with linear transparency and disc with nonlinear transparency along rotation angle based on Table 2.



Nominal%	Calibrated%
0.0	20.0
5.0	20.9
10.0	21.9
20.0	24.2
30.0	26.9
40.0	30.3
50.0	34.6
60.0	40.1
70.0	47.5
80.0	58.0
90.0	73.8
95.0	85.1
100.0	99.9

Figure 7. *Interface of brightness calibration software.*



a) b)

Figure 8. *Discs.*

a) linear transparency
b) nonlinear transparency

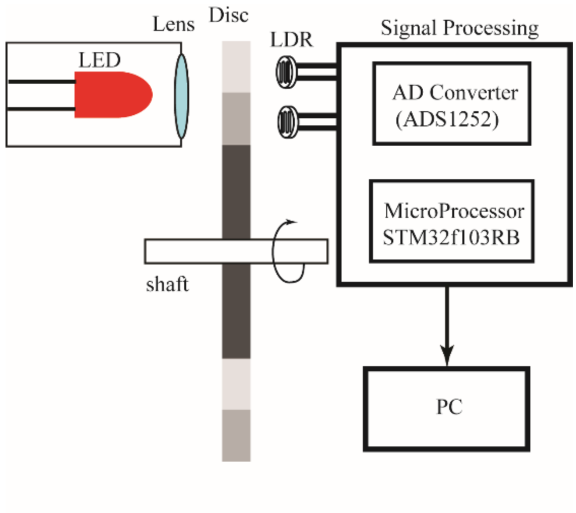
3. Experimental Setup and Result Analysis

3.1. Experimental Setup

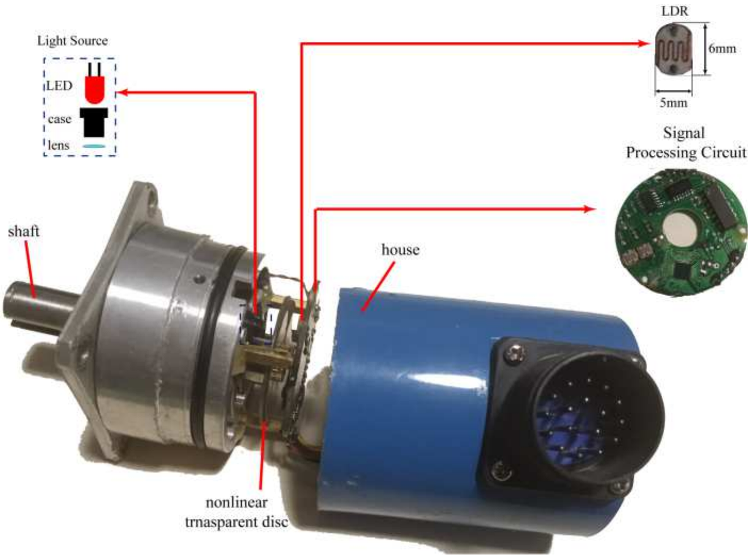
Figure 9 shows basic block diagram and photograph of absolute rotary angular sensor proposed in this paper.

As known in Figure 9, this absolute rotary angular sensor is composed with light source, lens, disc with nonlinear transparency, double LDRs and signal processing circuit with 24bit AD converter ADS1252 and microprocessor STM32F103RB.

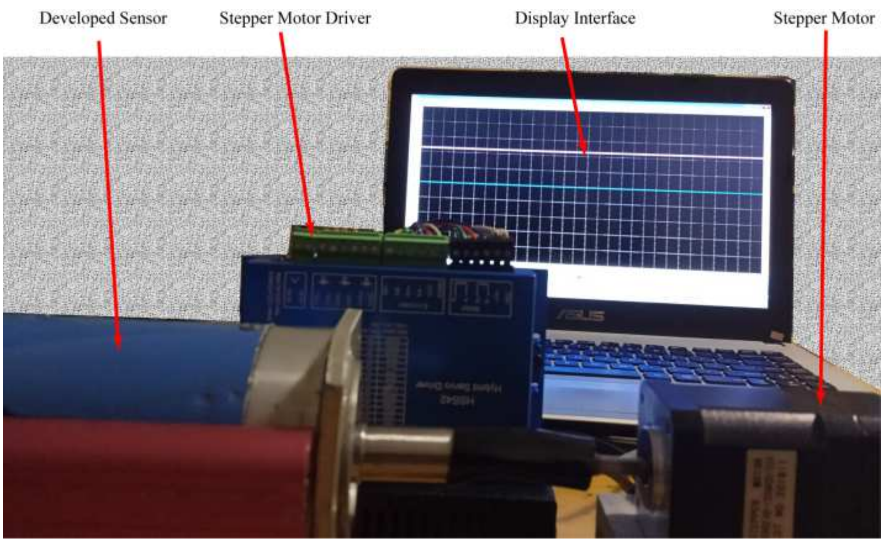
Disc is placed between LDR and light source. GaAlAs infrared light emitting diode TLDR5400 (Peak wavelength: 650nm, max Luminous intensity: 70mcd) is used as light source and lens is placed under light source for uniform incident light beam. So after passed through lens, light beam emitted from LED became a parallel light beam. As transparency of disc changes symmetrically across radius as shown in Figure 8, sensor presented in this paper is operated as resistive potentiometer and analogue signal is generated. This analogue signal is converted to digital signal and transferred to PC by signal processing circuit. Absolute rotary angular sensor has been evaluated by this digital data.



a) Basic block diagram



b) Photograph of absolute rotary angular sensor proposed in this paper



c) Experimental Setup

Figure 9. *Basic block diagram of proposed prototype.*

3.2. Results and Discussion

To evaluate the proposed absolute rotary angular sensor, measurement in whole range of rotation (0-360°) has been carried out. Measurement has performed in step of 10° by stepper motor 42HSE48-1504A05-D24 and driver HSS42. Figure 10 shows relationship between measurement data and true position. Measurement data shows an excellent linearity to real angle as known in Figure 10 (adjusted R-square statistics R^2 =0.9999). Sensor has 15bit *digital* data by AD converter ADS1252 and signal offset of processing circuit is 0.1°.

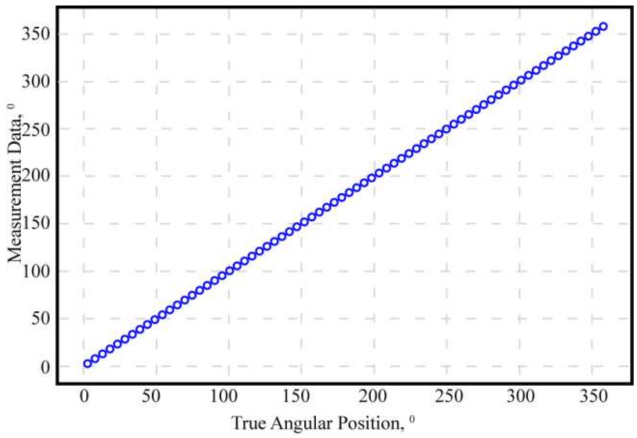


Figure 10. *Relationship between measurement data and true angular position.*

In evaluating the sensor, repeatability is a key parameter.

So this paper has been evaluated repeatability of the proposed sensor. To do this, rotary angle has been changed with step of 10° by step motor in whole range and measured in each angular position. These measurements are performed several times and differences in each angular position are calculated. Figure 11 shows result of repeatability measurement. As known in Figure 11, this sensor has a good repeatability in a range of 0-360° with maximum characteristic drift around ±0.1°.

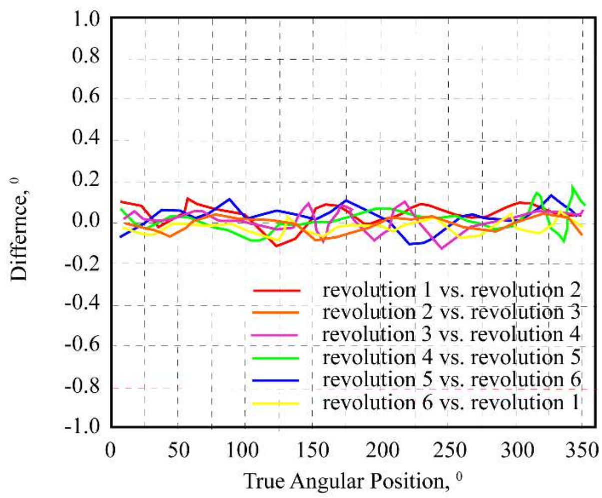


Figure 11. *Error between several repeated measurement.*

Figure 12 shows measurement error in proposed sensor. As well as other characteristics measurement, measurement error is accurately performed in step of 10° in entire measuring range (0-360°) by stepper motor. It is clear that measurement error is ±0.5° from Figure 12. It seems that measurement error exists as nonlinear gradient transparent disc proposed in this work is based on only 20 experimental data. Therefore, it is supposed that more experimental data is necessary to decrease measurement error.

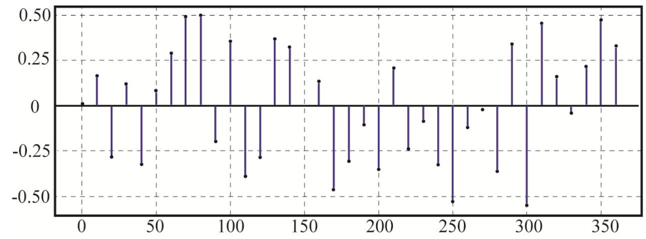


Figure 12. *Measurement error.*

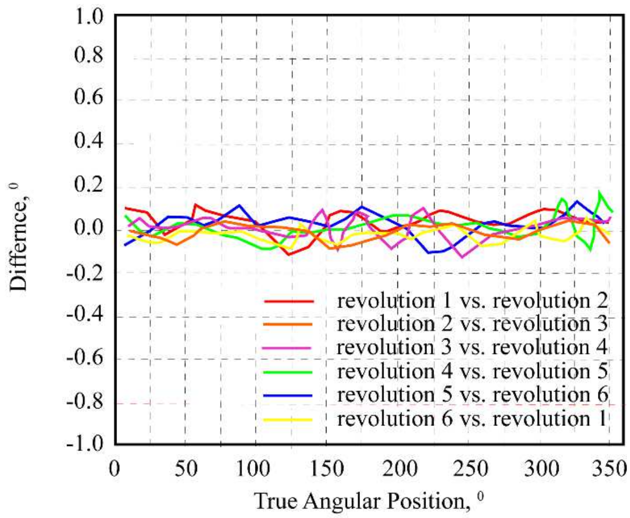


Figure 13. *Measurement stability during 1h.*

Figure 13 shows measurement stability of proposed sensor. Stability is evaluated by measurement data during 1h on a given angular position (for example, angular position is 45^0). As known in experimental result of measurement stability, measurement data has variance below $\pm 0.1^0$ in each true measurement position. It seems that these variances are generated by stepper motor's vibration and noise of signal processing circuit.

Operating speed of the proposed sensor (in terms of rpm) was not tested, since the main purpose of this paper is to demonstrate the idea for absolute rotary position measurement. In experiment, output resistance of LDR changes in the range of 8.1kΩ, detectable output is 2.5Ω and sensitivity is $0.225 k\Omega/^0$. So resolution of proposed sensor is 1^0.

4. Conclusion

Absolute rotary angular sensor proposed in this paper is a new type of noncontact potentiometer which consists of nonlinear gradient potentiometer and a couple of LDR. Experimental setup in order to demonstrate a proof of concept of the rotary position sensor is presented. And also, several characteristics of sensor such as linearity, repeatability and stability show. As known in experimental results, proposed sensor has a good linearity of R^2=0.99999, a good repeatability of maximum characteristic drift around ±0.1°, measurement error below ±0.5° and measurement stability is ±0.1°within its full operating range from 0° to 360°.

The proposed disc assembly and overall results can be helpful to design absolute rotary angular sensor for performance improvement of it. It seems that the proposed method has important practical significance for the development of optical absolute rotary angular sensor.

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