

Novel Absolute Rotary Position Sensor Based on Combination of Gray Scale Pattern Disc

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Abstract

Absolute rotary angular /position sensors play an important role in various applications and rapid development of new technologies requires further accurate measurement and control. In this paper, a novel, very simple, low-cost and high accurate absolute rotary angular/ position sensor is presented. The sensor operation is based on the combination of circular gradient gray scale and gray code pattern. A simple experiment is done in order to demonstrate proof of concept of proposed sensor. The experimental results show that the proposed absolute rotary angular/position sensor has excellent linear characteristics with accuracy below $\pm 1^\circ$ and resolution of 0.1° within the full measurement range from 0° to 360° . The proposed idea and experimental results can be helpful to design absolute rotary angular/position sensor to improve performance of it.

1. Introduction

Nowadays, rotary angular /position sensors play an important role in various applications such as automotive, robotics, automation for precise position control and etc. [1]. The rapid development of new industrial technologies requires further accurate position measurement and control for machining operations. Angular/ position sensors can solve such problems, providing high measuring accuracy, speed and reliability with various options of mathematical and logical signal processing [2]. Implementation of sensor with high accuracy, resolution and reliability for lower cost is challenge for researchers. Absolute rotary position sensors can be classified according to the physical principle used for the measurement, namely resistive, capacitive, magnetic and optical ones. The resistive rotary position sensor needs physical contact between the stator and the rotor, therefore, which results in contact noise, abrasion and instability [3].

Capacitive rotary position sensors are sensitive to external electric fields, contamination and variations in space between the electrodes and require complex signal processing circuit for reducing noise. Various design of capacitive rotary position sensor has been reported to simplify its construction and providing high accuracy. A low-cost smart capacitive absolute with high resolution is presented [4] and capacitive rotary sensor that can measure full rotor position i.e. 0° – 360° is developed [5, 6]. A contactless capacitive angular/position sensor composed of the capacitive sensing element, a signal processor and microcontroller with resolution better than 1 arcsec over range of 360° is presented [7]. Magnetic field based rotary sensors are sensitive to external magnetic fields, moreover, they tend to be rather complex or to impose special structural requirements [8]. An improved method for angular displacement estimation based on Hall-effect sensors for driving a brushless permanent-magnet motor is reported [9]. A novel contactless sensing principle based on the relative rotation of a small diametrically magnetized cylindrical or annular magnet and one hall-effect sensor is reported [10]. A magnetic rotary sensor with a resolution more than 4000 pulses per revolution in a magnetic drum with a diameter of 35mm is presented [11]. Optical rotary sensors, on the other hand, have become recognized as indispensable displacement/position sensor due to its high accuracy, light weight, small size and excellent immunity to electromagnetic interference. Optical rotary sensor classically have a binary code disc based on the gray

code in which there is only a single bit changing during a transition from one position to the next to minimize readout errors due to non-ideal transitions. Many improvements of the gray code based pattern is reported [12–15]. Digital absolute rotary sensors which are not only accurate, light, small, and insensitive to EM interference but also characterized by their high resolution are reported, however, in these sensors, the encoder design is complex and contains numerous parts such as several light sources or an array of photo-detectors in the detection scheme [16–20]. Image rotary position encoder needs image sensor and image processing system to decode the response of the sensor from the coded information [21–23]. Several analog optical rotary sensors with high resolution and accuracy are reported. A novel low cost design of sensor based on simple gray scale transformation of RGB colored hue wheel and decoder unit consists of three optical reflection type color sensors is presented [24]. An optical, analog, self-referencing, ratio-metric, smart rotary position sensor is proposed for avionic applications [25]. In this sensor, the position of rotation is determined by the ratio of the transmitted and reflected light powers. A new absolute rotary sensor is studied, which acts as a positional pointer over the array of photo-detectors based circular track [26]. In the sensor, disc have transparent and semi-transparent segment and by which light can go through with two different intensity levels.

In this paper, a novel, very simple and low-cost absolute rotary position sensor is presented. The disc assembly consists of a light source, photo-detectors and novel pattern disc. The disc is designed by combination of transmission type based on circular gradient gray scale and typical gray code. A very simple experiment is done to evaluate the performance of proposed sensor. Absolute rotary angular/ position is determined by simple mathematical transformations of analog and digital signal from photo-detectors. The sensor provides high resolution, accuracy and linearity within the full operating range of 0° - 360° .

2. Principle And Implementation Of Disc

The principle of this paper is based on sensitive characteristic of photo-detector to intensity of incident light. In a general, photo-detector such as photo diode and/or photo transistor is sensitive to intensity of radiant light from light source.

The radiant intensity of light source can be changed by regulation of current which flow through it and /or opacity (photo- resistant) of mask which is placed between the photo-detector and light source. From this, rotary position can be measured utilizing a disc which has variant opacity values against rotary angular positions under constant radiant intensity. Fig. 1 shows a linear gradient gray scale pattern mask and a simple measurement circuit for experiment. Silicon infrared light emitting diode QEE122 is used as the light source and silicon infrared phototransistor QSE113 is used as the photo-detector to minimize influence of ambient light for the measurement.

The radiant intensity of photo-diode is correlated with the forward current (I_f) of it. Therefore, the radiant intensity can be changed by regulating of the forward current.

The measurement is done in six stages with different forward current of 2, 2.5, 3, 4, 5, and 10mA. In Fig. 2, the measurement results of output voltage for different forward current (radiant intensity) of light source are shown.

(a: $I_f=2\text{mA}$, b: $I_f=2.5\text{mA}$, c: $I_f=3\text{mA}$, d: $I_f=4\text{mA}$, e: $I_f=5\text{mA}$, f: $I_f=10\text{mA}$)

As shown in Fig. 2, the output voltage curve versus opacity of mask is nonlinear in full measurement range (opacity of 0-100%). Saturation regions exist in the voltage–opacity characteristics up opacity of 90% and below measured voltage (collector emitter voltage) of 0.5V. However, the characteristics in Fig. 2 have linear regions with different range. Therefore, linear output voltage characteristic can be obtained by proper regulation of opacity of mask and radiant intensity of light source. Fig. 3 shows output voltage measured versus opacity range of 35~85% in forward current of 4mA. As shown in Fig. 3, the characteristic curve shows good linearity. By introducing this for disc pattern, linear analog signal can be achieved for rotary angular position. In this case, the sensor's characteristics of resolution, accuracy and stability are relative to uniformity of gradient gray scale pattern, stability of measurement circuit and number of bits of analog to digital (A/D) converter. In Fig. 3, the output voltage variation is in range around 0.5-4.5V and it is enough for understandable resolution of the sensor without amplification. Also, the measurement circuit is very simple and so it is stable.

On the other hand, resolution of rotary position sensor with binary code pattern disc such as gray code is generally relative to the number of traces on the disc. And, it is necessary to increase the number of the traces (number of photo-detectors) to increase the resolution of the sensor.

From this, high resolution and linear characteristic can be obtained by combining small number of traces gray code with gray scale and its resolution is increased as 2^n (n is number of gray code traces) times as the single gray scale pattern disc. Also, the accuracy of it can be increased. Adobe Photoshop software is utilized to design gray scale pattern (Fig. 4). The gray scale pattern is simply conducted by utilizing the software but the most important key is the uniformity in each gradient gray scale partitions on disc. The printing of gray scale pattern is well done by using film printer Premmiter-102. As shown in Fig. 5, the outermost trace of the disc (b, c and d) is designed as reflected gray scale pattern partitions divided by binary code pattern to minimize readout errors due to non-ideal transitions of analog signal.

The diameter of disc is 40mm and the width of trace is sized of 3mm considering of geometrical dimension of photo-detector. In Fig. 6, photograph of novel pattern disc is shown.

3. Experiment And Discussion

Figure 7 shows the graphical setup of the proposed absolute rotary position sensor for experiment.

The proposed sensor is composed of three parts: disc assembly, signal processing circuit and a PC based analyzing software. The disc assembly consists of a light source, photo-detectors and disc. The disc is placed in between of the light source photo-detectors. Silicon infrared phototransistor QSE113 and silicon

infrared light emitting diode QEE122 are used for the light source and photo-detector, which are represented in section 2, respectively. Wavelength of the light source is 880nm and the forward current of it is 4mA. The photo-detectors are connected with the signal processing circuit to convert their signals into binary and analog. Subsequently, the analog signal is led to the 10 bit analog to digital (A/D) converter embedded in Pic16f873a microprocessor and the binary and A/D conversion results are transferred via serial communication to PC for further process. Calibration is done in order to measure and adjust the response of the proposed rotary position sensor. First, normalization of the opacity range (35% ~ 85%) of gray scale disc is done in order to simplify calculation of position for the proposed sensor. Next, transfer characteristic is constructed using these two data of measured voltage and normalized opacity in order to get opacity (position) calculation versus measured voltage (Fig. 8).

In Fig. 8, the x axis is for measured output voltage from photo-detector and the y axis is for normalized opacity. As shown in Fig. 8, the transfer characteristic is linear function and not polynomial. Therefore, the theoretical resolution of proposed rotary position sensor can be calculated by:

$$R = \frac{360^\circ}{2^n \times 1023} \times \frac{V_{max} - V_{min}}{V_{ref}}$$

1

In Eq. (1), n is number of binary code traces, V_{max} and V_{min} are maximum and minimum voltages in measured data and V_{ref} is reference voltage of A/D converter.

From measured data in Fig. 3 and Eq. (1), therefore, calculated resolution of proposed sensors are 0.26° , 0.13° , 0.07° and 0.03° for four discs in Fig. 5, respectively.

(a: single, b: one reflected-two region, c: two reflected-four region, d: three reflected-eight region)

Measurement results of output voltage for analog signal in different gray scale pattern disc (single gray scale partition, two reflected gray scale partitions, four reflected gray scale partitions and eight reflected gray scale partitions) are shown in Fig. 10.

In test of proposed rotary position sensors, the disc is rotated manually to simplify the replacement of it. Measurements are performed in step of 15° for one full revolution of the disc. In Fig. 10, the characteristics of the proposed absolute rotary position sensors with different patterned disc are shown. In Fig. 10, the calculated positions are given after normalization and compensation using the transfer characteristic presented in previous section. The characteristics of the proposed rotary position sensors are drawn by using binary and normalized and compensated analog signals using the equation in Fig. 3. As shown in Fig. 10, characteristic curves show good linearity for the entire measuring range (0° – 360°). Offset of the proposed rotary position sensor is less than 0.5° . Fig. 11 presents the measurement error of the proposed rotary position sensors with different disc. As well as the characteristic of the proposed sensors, the measurement error is also recorded in step of 15° in the full operating range (0° – 360°).

The measurement errors exist within $\pm 2.2^\circ$, 1.5° , 0.9° and 0.8° for four designed disc, respectively. Furthermore, the measurement errors of c) and d) in Fig. 9 are even less than $\pm 1^\circ$ with a very simple experiment setup given in this study. Also, only opacity range of 35%-85% and constant radiant intensity (forward current of 4mA) is considered in this experiment.

It is supposed that even less error can be achieved by more precise device fabrication for this application. Only, the main purpose of this work is to give a proof of concept of the rotary position sensor.

In Fig. 12, variation of maximum and average rotary position error of the propose sensors with different number of traces pattern disc. Fig. 12 shows that the increase of number of traces results in the decrease of error (maximum and average). However, it is estimated that there is no more decrease of error for increase of number of traces on disc.

For evaluating the precision of the sensor, repeatability/stability testing is performed. Fig. 13 shows the measurement repeatability/stability of the proposed rotary position sensor with 3- binary traces, gray scale trace pattern disc. The repeatability/stability is recorded during one hour captured 3 times per minute (every 20s). As shown in Fig. 13, excellent repeatability/stability is achieved with maximum characteristic drift around of $\pm 0.2^\circ$. 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.

4. Conclusion

In this paper, very simple, low cost and high precise absolute rotary angular/position sensor is designed, implemented and tested. The operation of the proposed sensor is based on the combination of circular gradient gray scale and binary code (gray code) pattern. In this work, very simple experimental setup in order to demonstrate a proof of concept of the rotary position sensor is presented. It is supposed that even better performance can be accomplished with more precise device manufacturing. The proposed prototype manufacturing cost has been determined even less than \$10 (for experiment only). Moreover, performance parameter of the proposed rotary sensor exhibits good linearity, repeatability/stability of $\pm 0.2^\circ$, accuracy of $\pm 1^\circ$ and resolution below 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/position sensor for performance improvement of it.

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Declarations

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Figures

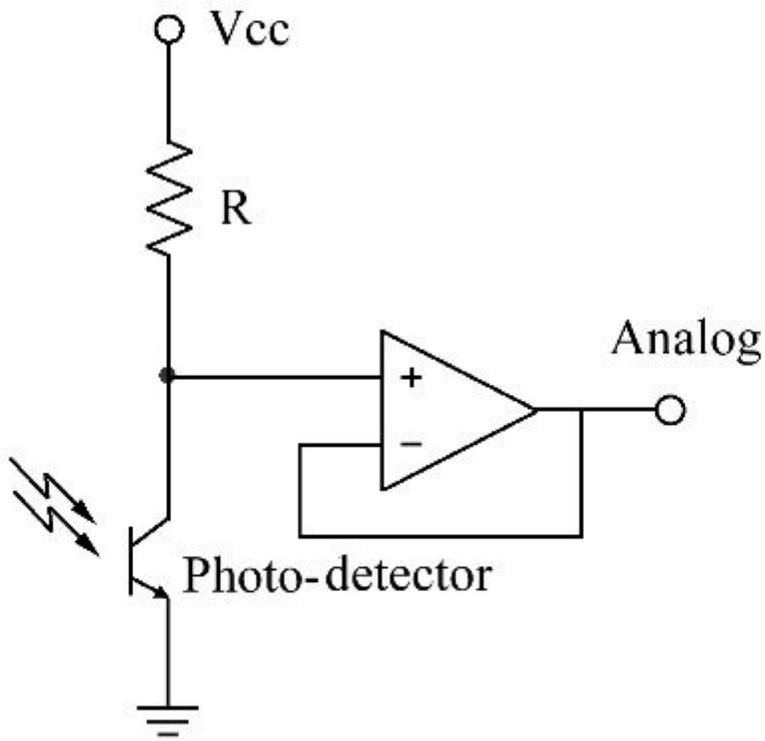
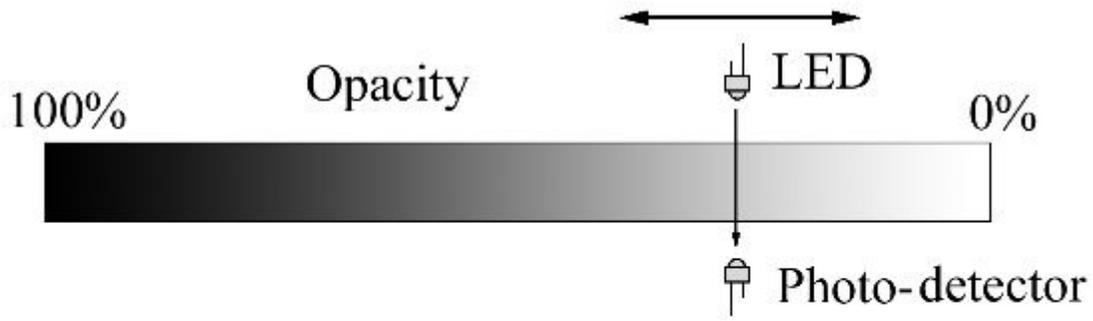


Figure 1

Principle of operation

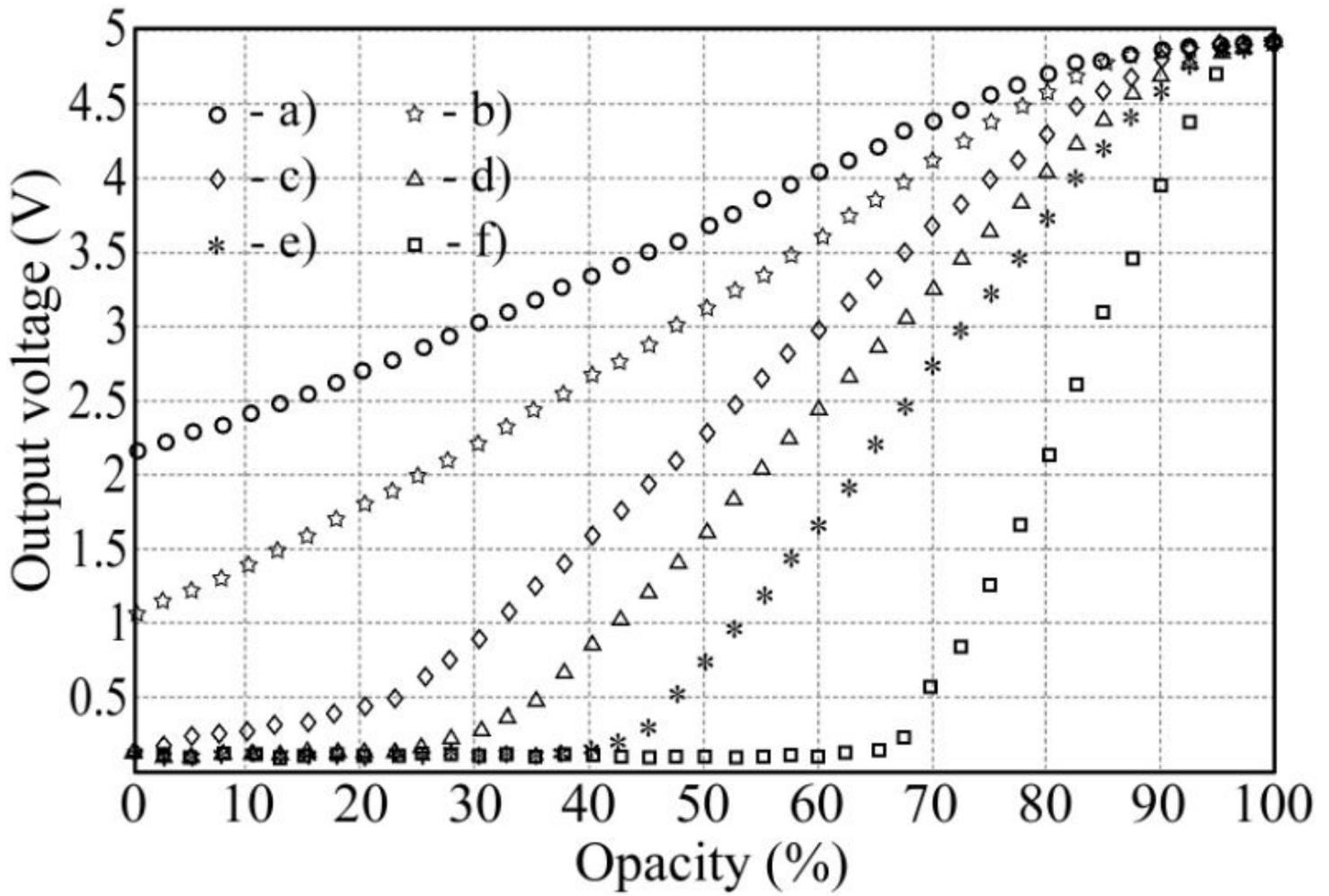


Figure 2

Measurement results (a: $I_f=2\text{mA}$, b: $I_f=2.5\text{mA}$, c: $I_f=3\text{mA}$, d: $I_f=4\text{mA}$, e: $I_f=5\text{mA}$, f: $I_f=10\text{mA}$)

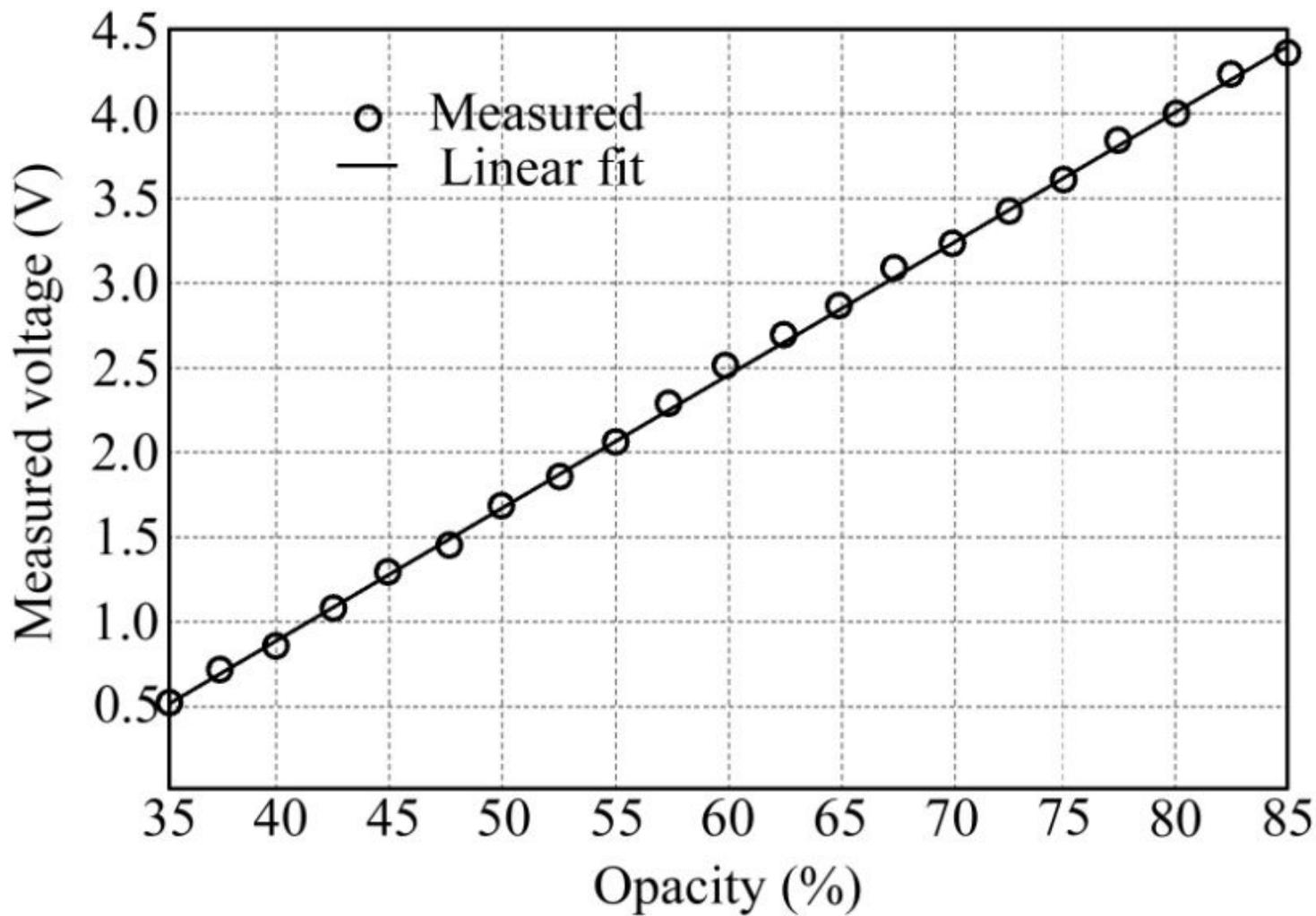


Figure 3

Measured voltage versus opacity range of 35~85% in forward current of 4mA

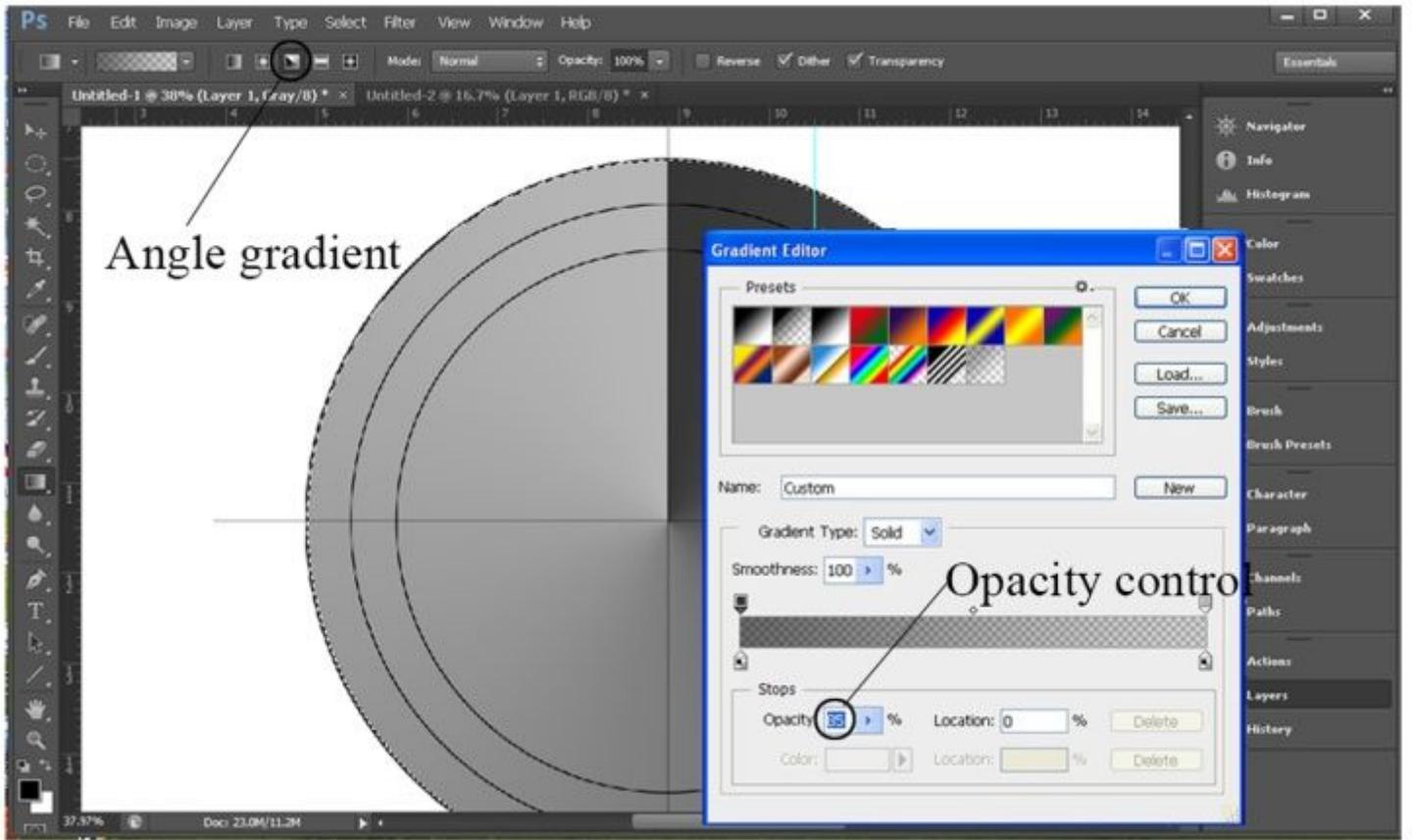


Figure 4

Adobe Photoshop design interface for pattern disc

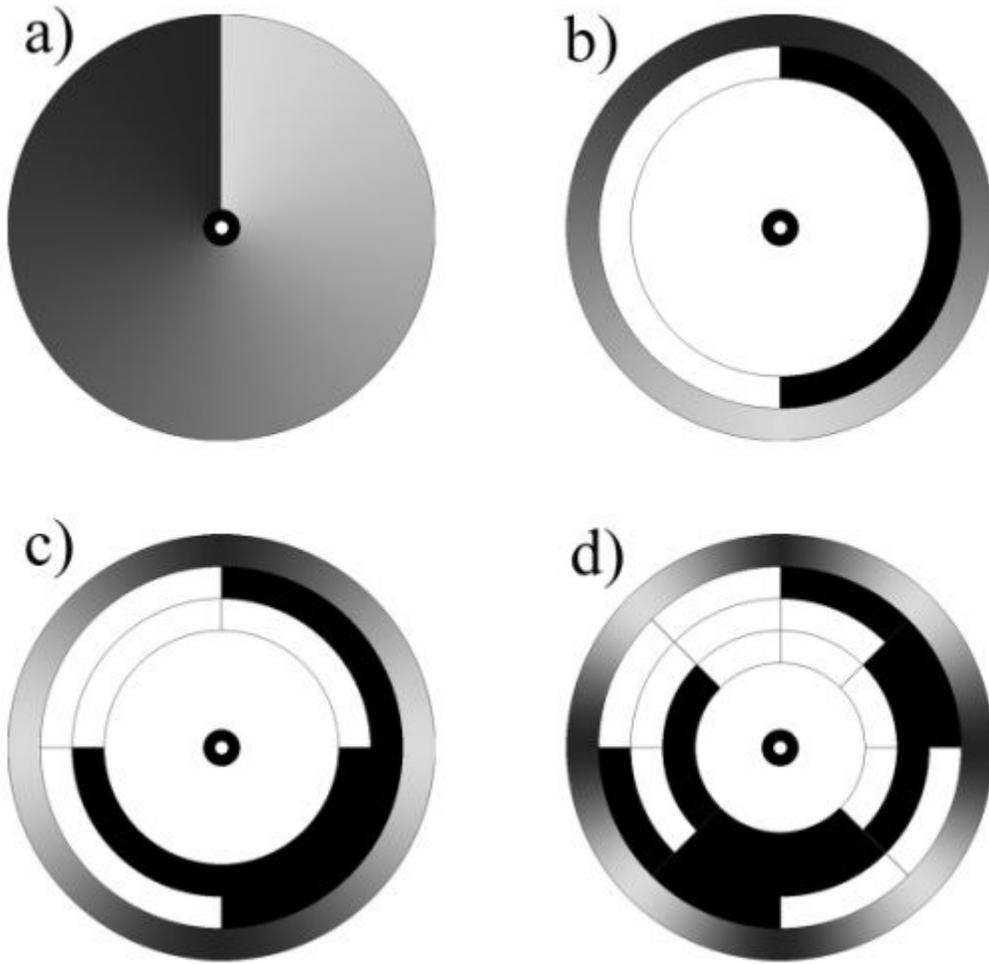


Figure 5

Gray code and gray scale pattern (a: single gray scale pattern, b: 1- binary trace, gray scale pattern, c: 2- binary traces, gray scale pattern, d: 3- binary traces, gray scale pattern)

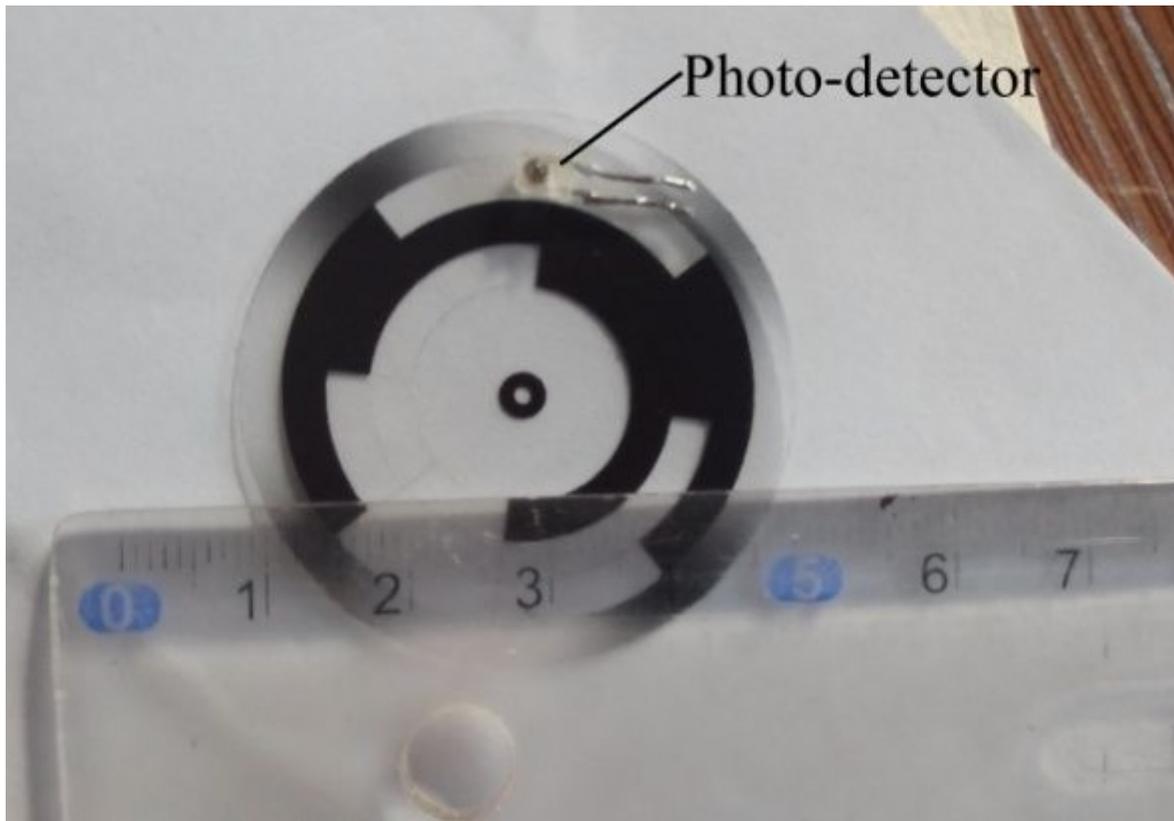


Figure 6

Novel pattern disc

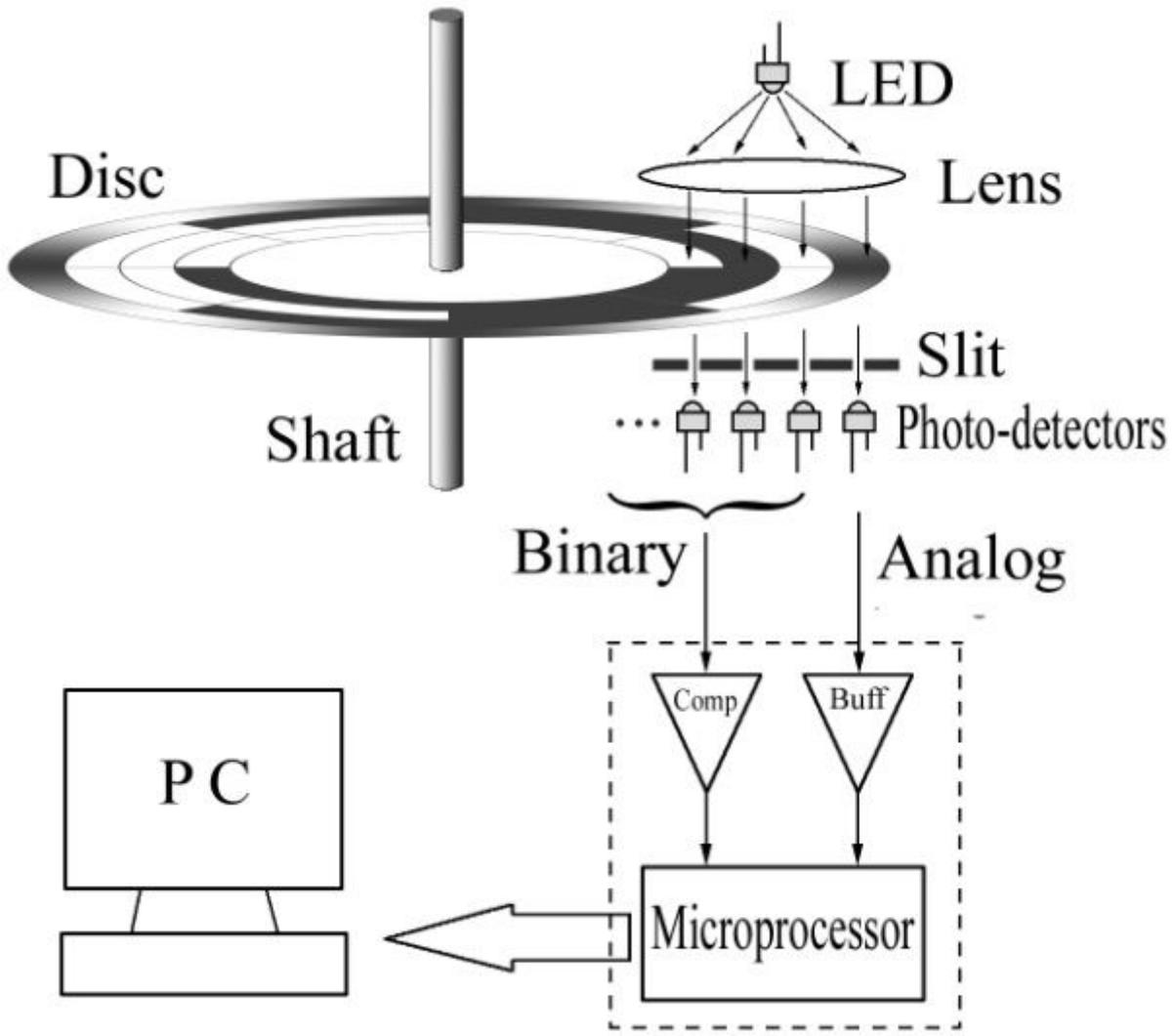


Figure 7

Graphical setup of proposed sensor for experiment

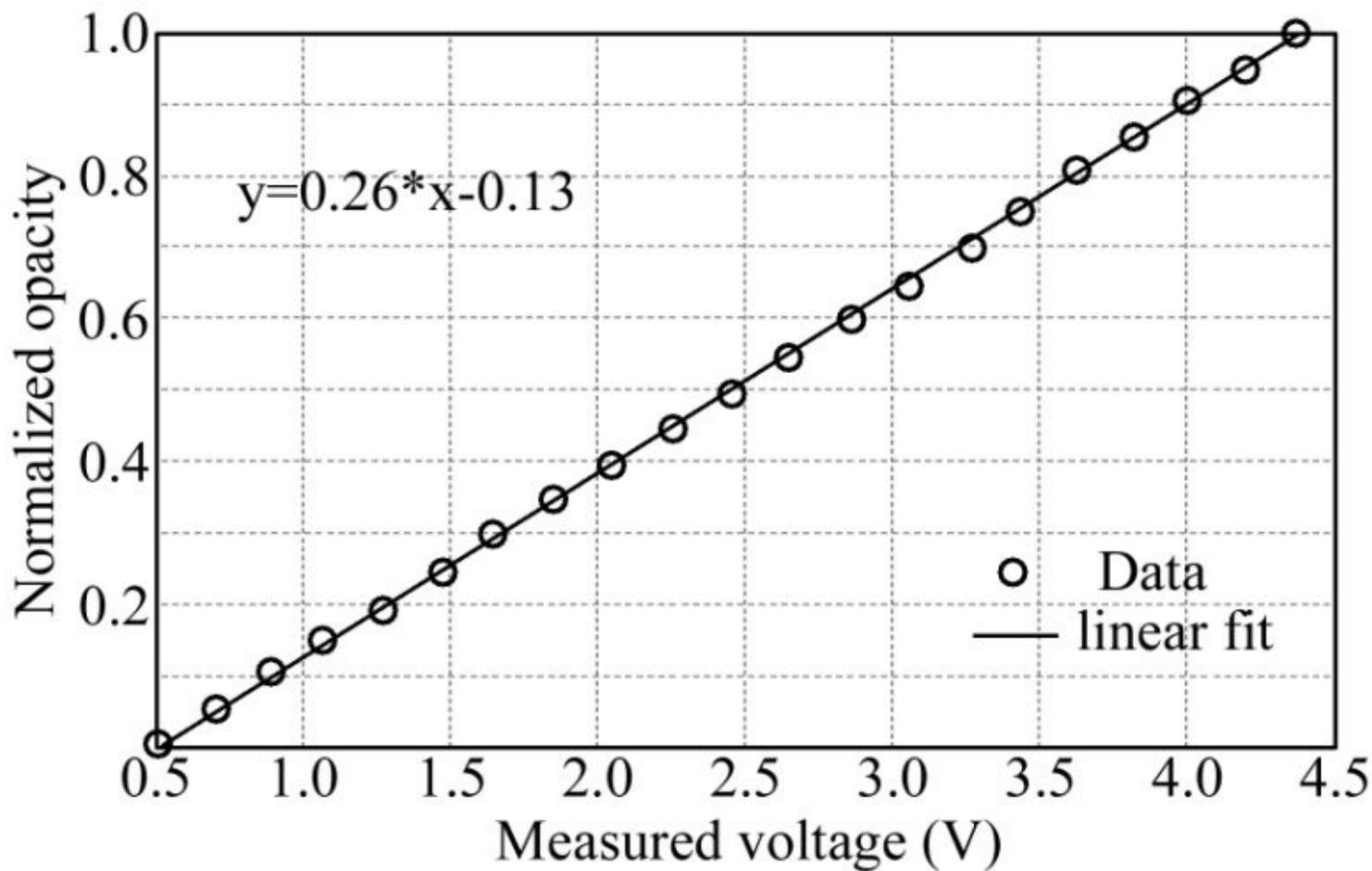


Figure 8

Transfer characteristic

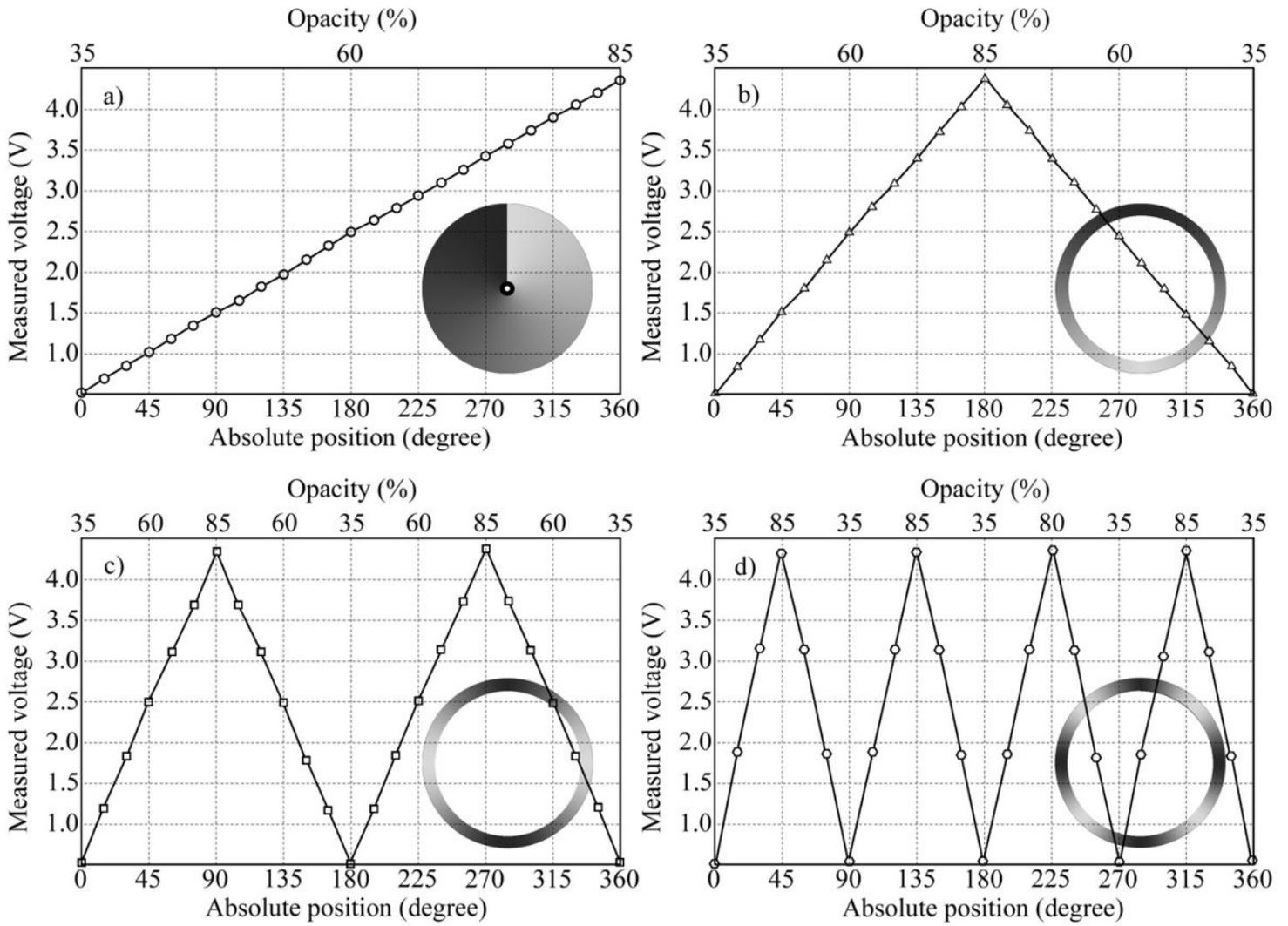


Figure 9

Variations of output voltage for different pattern disc

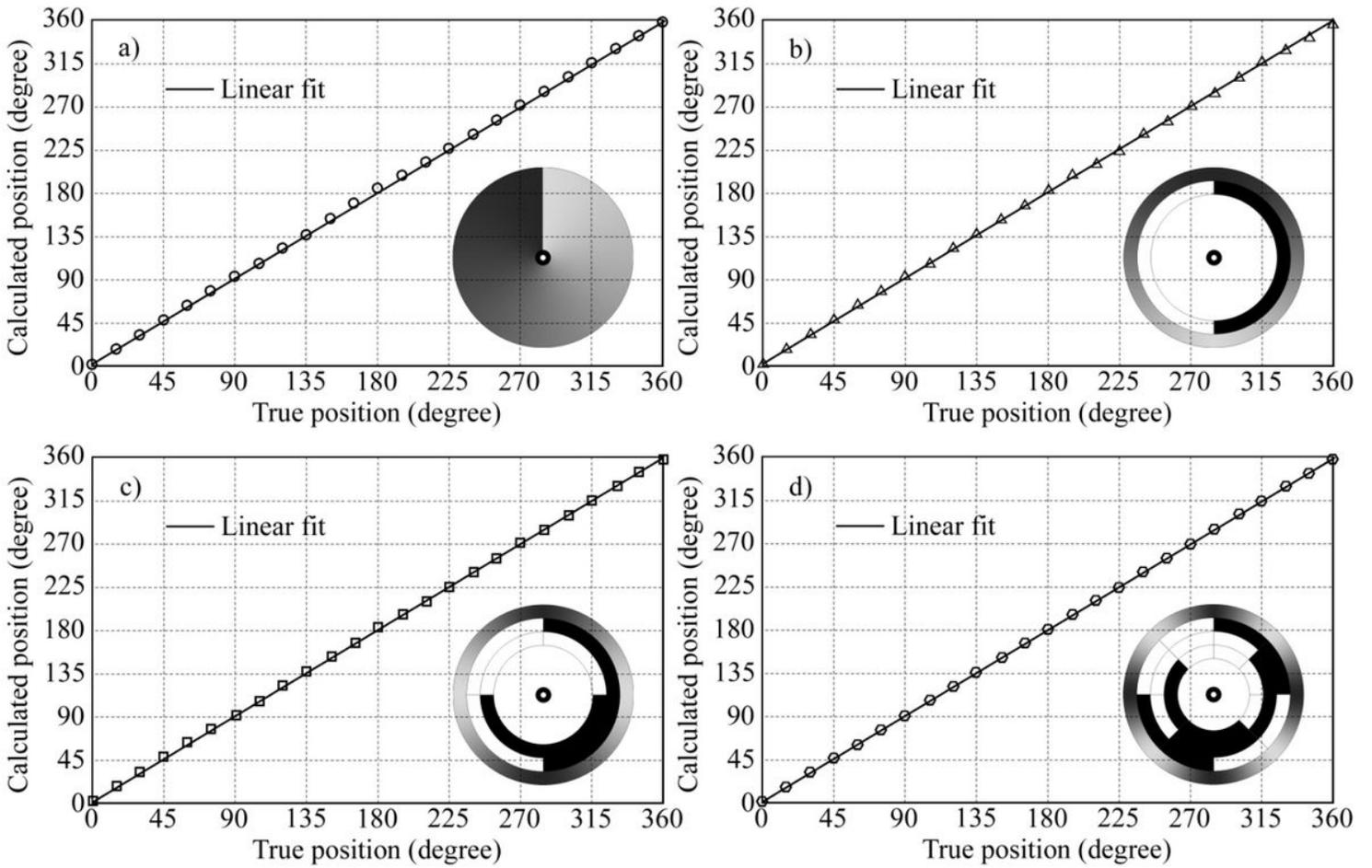


Figure 10

Characteristics of the proposed absolute rotary position sensors with different pattern disc (a: single gray scale, b: 1-binary trace, gray scale trace, c: 2- binary traces, gray scale trace, d: 3- binary traces, gray scale trace)

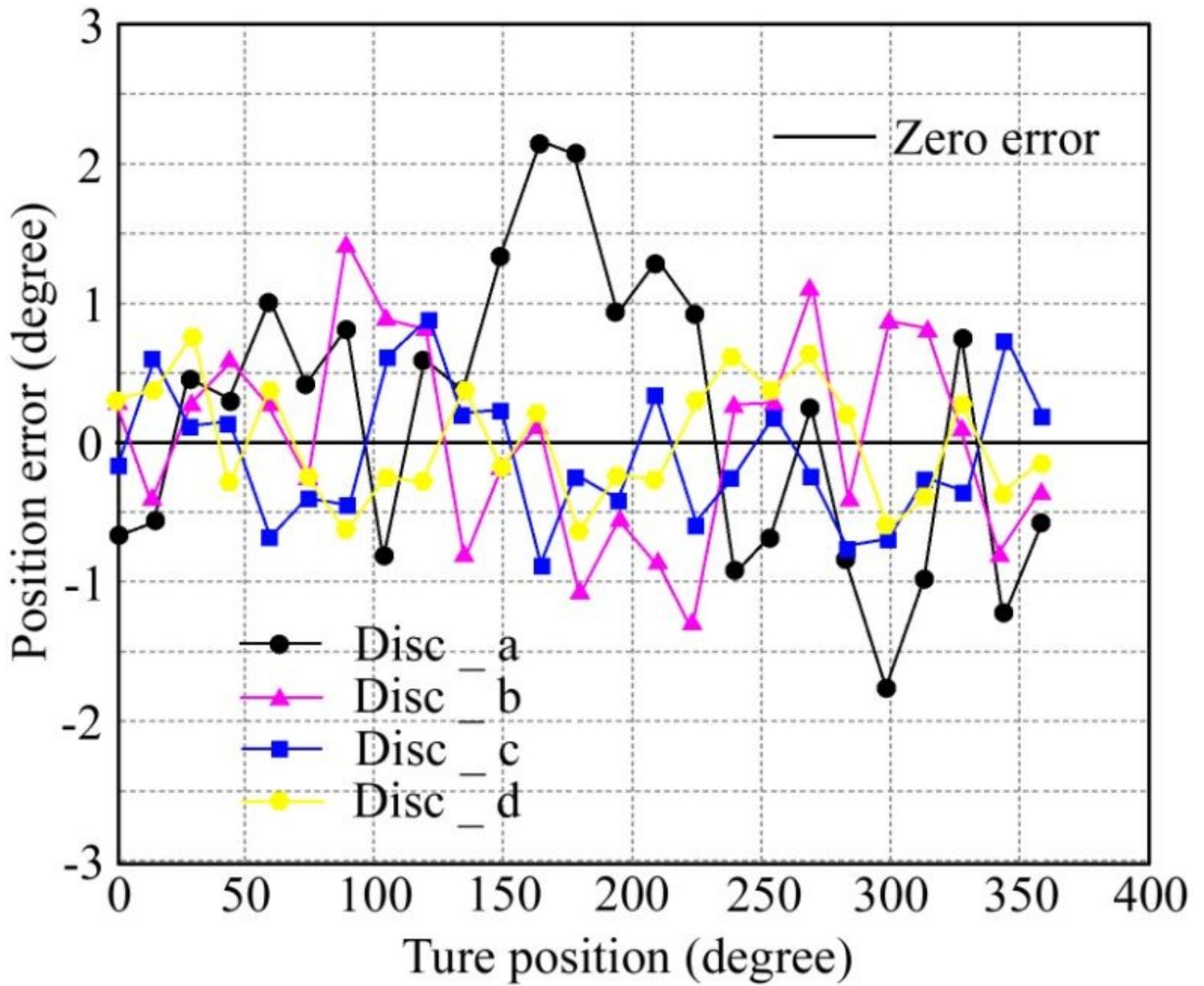


Figure 11

Measurement error

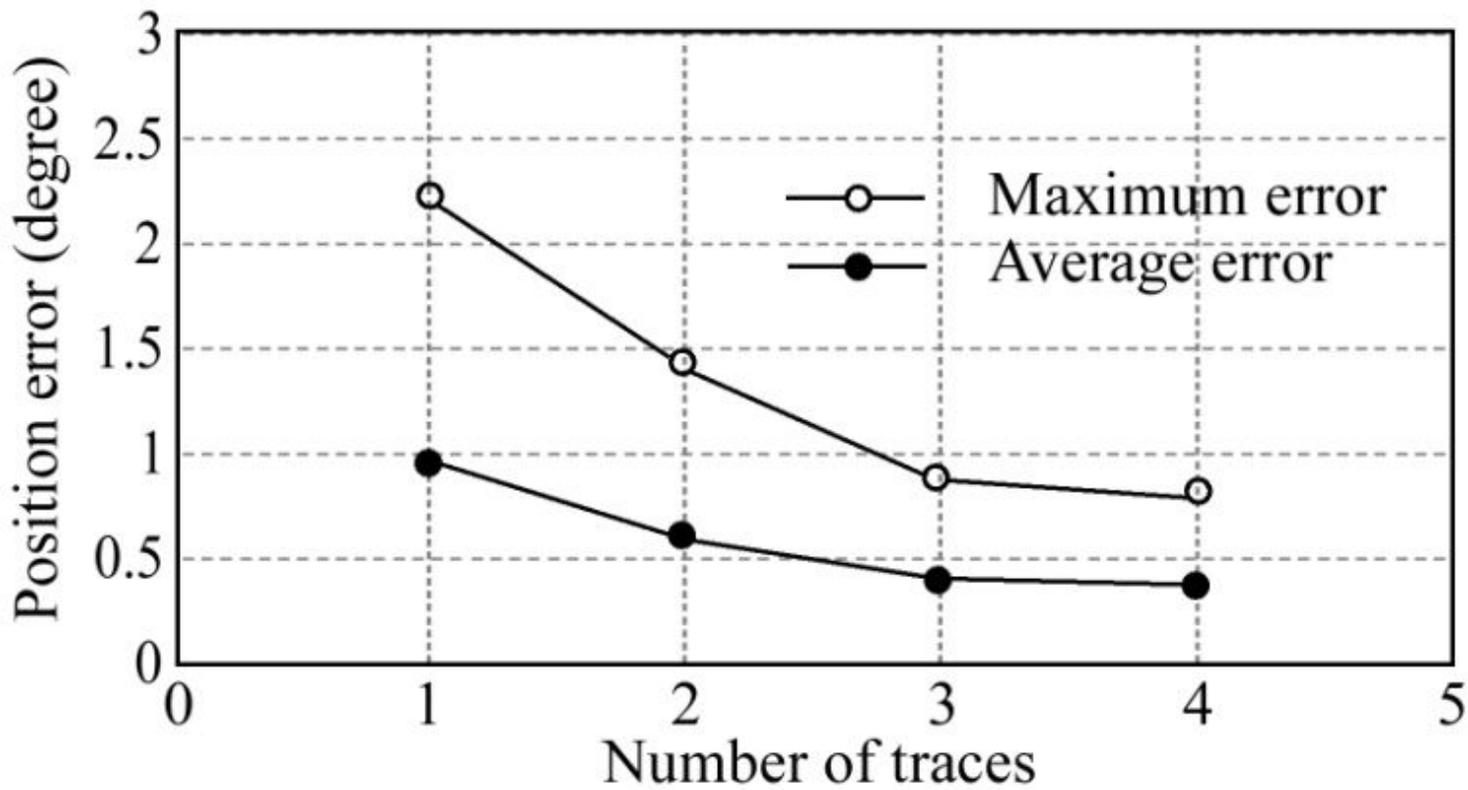


Figure 12

Variation of measurement error

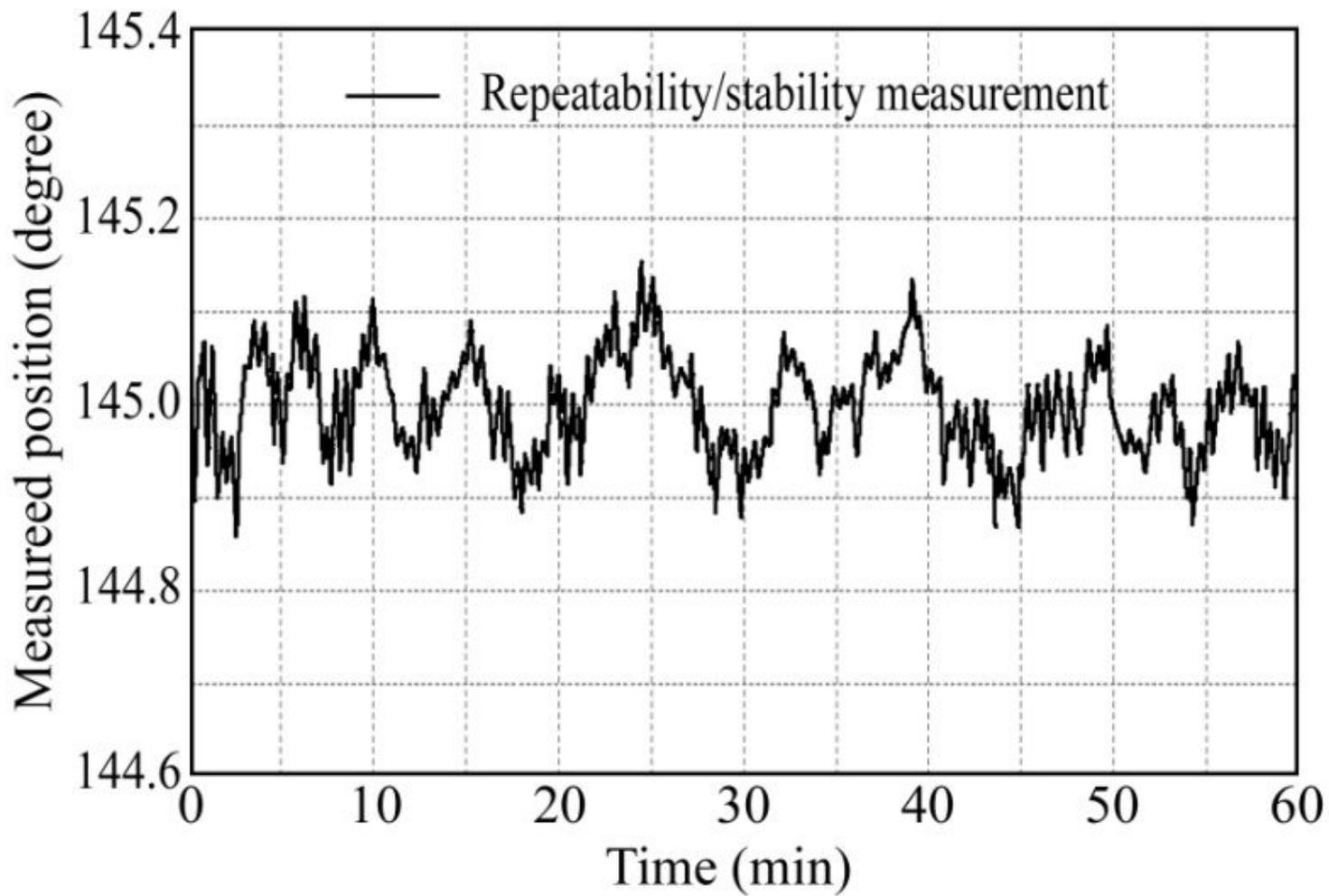


Figure 13

Measurement repeatability/stability during 1 h