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# Increasing of Excursion Range of Absolute Optical Sensors Intended for Positioners

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**Abstract:** In the present paper we consider an optical linear sensor with a new structure, which allows for increasing its excursion range. Such a sensor is applied in positioners for precise measuring of linear displacement. The developed analytical model of such a device provides a possibility of preliminary theoretical analysis and developing an algorithm, correcting the appeared significant nonlinearity of sensor volt-displacement characteristic and thus reducing the positioner instability. Consequently, the suggested sensor can be successfully embedded in a closed-loop control system of a linear positioner with increased linear displacement. In the paper an example of a positioner with this sensor is described. A comparison of the computed and experimentally measured results is also given. *Copyright © 2009 IFSA.*

**Keywords:** Absolute position sensor, Sensor scale factor, LED, Photodiode, Positioner

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## 1. Introduction

An absolute optical sensor (AOS), based on evaluating the intensity of the incident light, is an efficient means for measuring linear displacements in electro-mechanical closed-loop position control systems (positioner) [1, 2, 3]. Such sensors comprise a light source (LED or a laser) and a detector of a light intensity (often a silicon photo diode. The intensity of the light reaching the detector is determined by the displacement of the controlled actuator. In contrast to incremental encoders [4], AOS are absolute position sensors; they are simple, cheap and work in a wide temperature range. The main disadvantages of AOS implementation in positioners are [5]:

a) temperature dependence of the light intensity emitted by the source;
b) non-uniform spatial distribution of the light intensity emitted by the source;
c) limited longitudinal dimension of the photo detector, measuring the light intensity.

Characteristics a) and b) affect the stability of the closed-loop control system, since the sensor's scale factor turns out to be non-constant, but rather dependent on the actuator position and the temperature. Disadvantage c) restricts the application area of AOS to positioners having a small linear displacement. Property a) can, in practice, be dealt with by using an additional (constant aperture) photo detector, which allows significant decrease of the temperature dependence [6].

The structure analyzed in this paper was proposed in order to increase the sensor's excursion range, achieved by using two overlapped photo-detectors, thus allowing relatively large measurement range despite property c). This, in turn, leads to strong irregularity of the scale factor, which is an inevitable result of the overlapping. Such drawback can be fixed by a properly composed correction algorithm, which is required for providing stable operation along the complete excursion interval. The sequel describes a method for analyzing and computing the resulting scale factor and subsequently designs a corrective element in the control scheme. This process eventually allows for an absolute sensor applicable in a significantly wider class of positioners, including those having a long linear displacement.

## 2. Theoretical Model

The LED light source is a principal element of the sensor, therefore the analysis begins by modeling its characteristics. An angular dependence of the luminance for a typical LED (SFH421, [7]) is presented in Fig. 1.

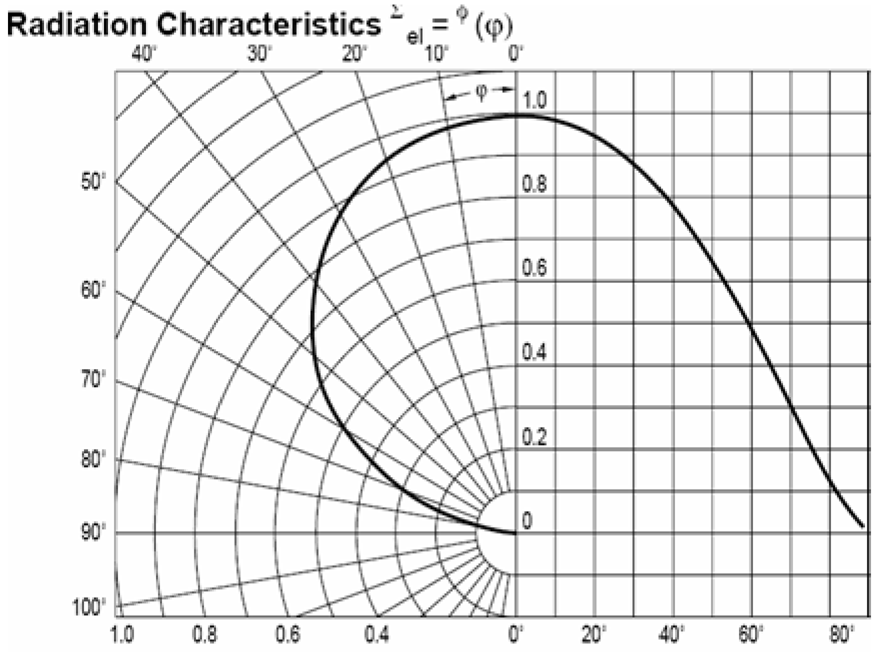


**Fig. 1.** Angular radiation characteristic for the LED SFH421.

In a general case the luminance angular dependence can be approximated by a polynomial function:

$$I(\varphi) = c_0 + c_1\varphi + \ldots + c_n\varphi^n,$$

however for our specific choice the angular interval of interest this dependence can be described by a second order function $I(\varphi) = c_0 + c_1\varphi + c_2\varphi^2$. Furthermore, the angular displacement $\varphi$ can be described as a function of the distance *r*, $\varphi\left(r/D\right)$, where $r = \sqrt{x^2 + y^2}$, and *D* is the (fixed) distance between the LED and the coordinate plane (*x*, *y*).

By integrating at the receiver aperture: 0 ≤ x ≤ X, 0 ≤ y ≤ B (see Fig. 2), one can obtain the signal of the sensor as a function of the shutter position *S*(*X*).

$$S(X) = 2\int_{-B/2}^{B/2}\int_{0}^{X} I(x, y)\,dx\,dy \tag{1}$$

Once S(X) is computed (or approximated), it can be used to compute the derivative $\frac{d}{dX}\left(S(X)\right)$ which is the actual scale factor (SF) of the AOS when used as a feedback sensor. If the accuracy of the computation and approximation is good enough, it can be used in order to correct in real time the sensor's reading, thus overcoming the inherent non-linearities arising when combining several such sensors in order to increase the overall AOS range.

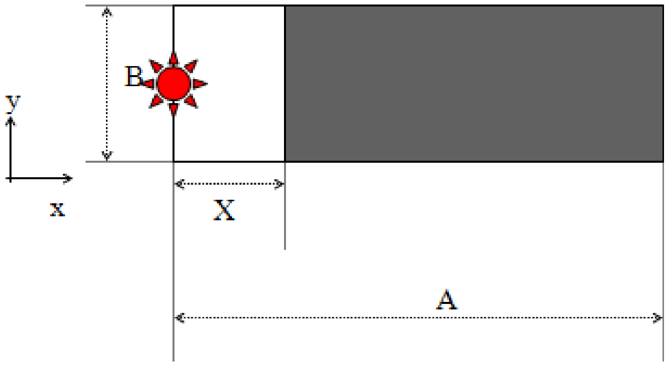
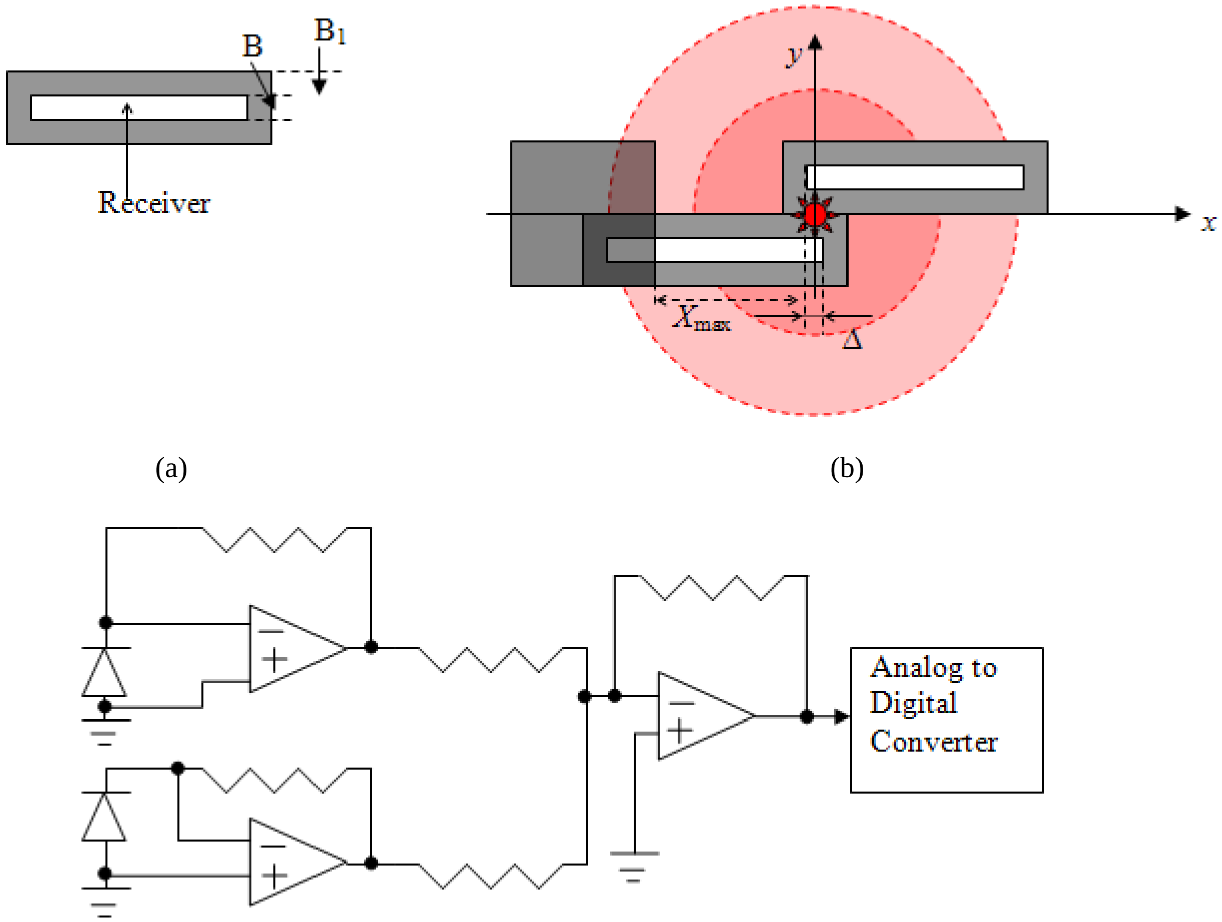


**Fig. 2.** The scheme of a single slot absolute sensor.

Next we demonstrate luminosity computation for an actual sensor, followed by theoretical of the respective SF. The latter is then compared to experimental testing results of the sensor. Finally, nonlinearity on-line correction is demonstrated using the derived SF.

For the actual testing, the structure presented in Fig. 3 was used, where two overlapped AOSs S7509 [8] are combined to increase the sensor's range. The electronic scheme depicted in Fig. 3 (c) provides the output digital signal, which depends on the actuator linear displacement. The light source is an SFH421 LED (Fig 1). In this case and within an angular interval of 0 ° – 24°, which is the area of interest, one can approximate $\varphi(r/D)$ as

$$\varphi(r, D) = \frac{r}{D} - \frac{1}{3}\left(\frac{r}{D}\right)^3 + \mathrm{O}(0.007) \tag{2}$$



(a) (b)

(c)

**Fig. 3**. The experimentally tested double slot absolute sensor: (a) slit detector, (b) overlapped AOS sensor. Here *B*=2 mm, $B_1$=6.5 mm, *A*=10 mm, *D*=11 mm, Δ=0.2 mm, (c) the electronic scheme for digitizing the output signal in the overlapped AOS.

And eventually

$$I(r) \approx c_0 + c_1 \frac{r}{D} - c_1 \frac{1}{3}\left(\frac{r}{D}\right)^3 + c_2 \frac{r^2}{D^2} - \frac{2}{3} c_2 \frac{r^4}{D^4}, \tag{3}$$

where for the chosen LED $c_0 = 1$, $c_1 = 0.035$, $c_2 = -0.5$ for the normalized intensity. For such parameters the 3d order term in (3) can be dropped because of the small value of $c_1$. See Figure 3 for definition of the other parameters.

One can proceed now to compute *S(X)* (eq. 1). The maximal value of *X* (see Fig. 3) can be estimated as

$$X_{\max} = \frac{\Delta}{2} + \sqrt{D^2 \tan(\varphi_{\max})^2 - \left(\frac{B_1 + B}{2}\right)^2} \tag{5}$$

Relation (5) the value $X_{\max}$=2.25 mm with the relative error ΔS/S≤ 0.01, where Δ*S* is the absolute error in calculation of *S*, originated from restriction of the integration interval in (1). However, reducing the required accuracy as ΔS/S≤0.05 will allow for dealing with wider angular interval resulting in $X_{\max}$=7.8 mm.

Applying equation (1) to the structure in Fig 3 (b) requires slight modification:

$$S_1(X) = K \int_{(B_1-B)/2}^{(B_1+B)/2} \left\{ \int_{-\Delta/2}^{A-\Delta/2} I(x,y)dxdy + \int_{X}^{\Delta/2} I(x,y)dxdy \right\} \tag{6-1}$$

for $X < -\Delta/2$,

$$S_2(X) = K \int_{(B_1-B)/2}^{(B_1+B)/2} \left\{ \int_{X}^{A-\Delta/2} I(x,y)dxdy + \int_{X}^{\Delta/2} I(x,y)dxdy \right\} \tag{6-2}$$

for $-\Delta/2 \le X \le \Delta/2$

$$S_3(X) = K \int_{(B_1-B)/2}^{(B_1+B)/2} \int_{X}^{A-\Delta/2} I(x,y)dxdy \tag{6-3}$$

for $X > \Delta/2$. Here $K$ is the factor, characterizing the transformation of the illuminating intensity to the digital signal $S$. Really it is determined by the optical characteristics of the LED and the detector's sensitivity and accepted units of the signal. In our case we specify this parameter below by using the measuring value of $S$.

Experimental results of testing the AOS sensor depicted in Fig. 3 are shown in Fig. 4 and Table 1.

**Table 1.** Experimental results of the test.

| **Displacement [mm]** | **S(X)** | **\|dS/dX\|** |
|---|---|---|
| -8.5 | 63480 | 1898 |
| -7.5 | 61207 | 2273 |
| -6.5 | 58455 | 2752 |
| -5.5 | 54928 | 3527 |
| -4.5 | 51094 | 3834 |
| -3.5 | 47131 | 3963 |
| -2.5 | 42982 | 4149 |
| -1.5 | 38773 | 4209 |
| -0.5 | 34335 | 4438 |
| 0 | 30299 | 8072 |
| 0.5 | 26263 | 4492 |
| 1.5 | 22062 | 4201 |
| 2.5 | 17951 | 4111 |
| 3.5 | 14056 | 3895 |
| 4.5 | 10327 | 3729 |
| 5.5 | 6810 | 3517 |
| 6.5 | 4128 | 2682 |
| 7.5 | 1940 | 2188 |
| 8.5 | 50 | 1890 |

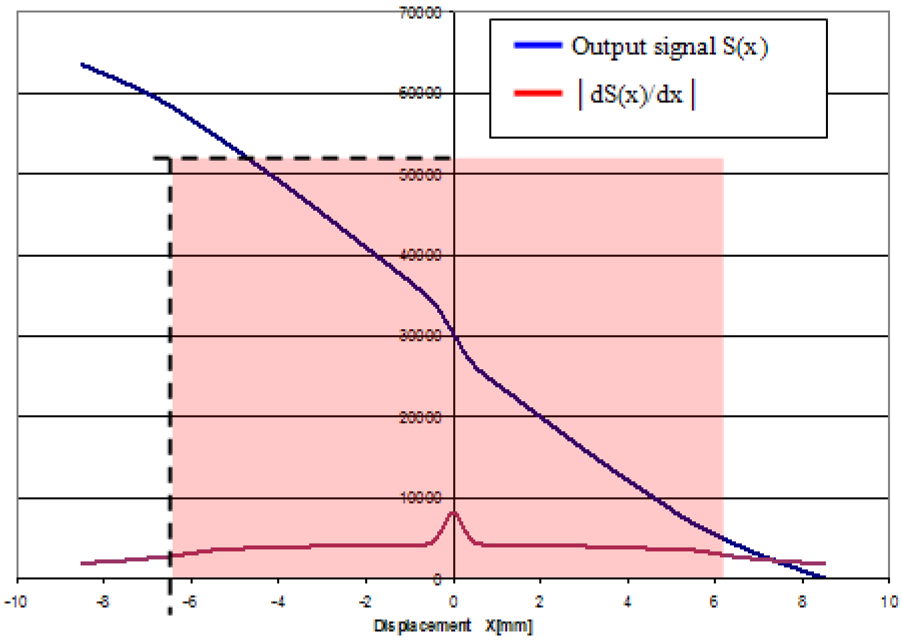


**Fig. 4.** Experimental characteristics of the overlapped sensor: the blue line shows the output signal S(x) and the red line is the scale factor |dS/dx|.

Actually, the edges of the receivers have *x*-coordinates that are out of the interval -$X_{\max} < X < X_{\max}$ defined for the required accuracy of our analytical estimations. Consequently, it is more convenient to use the derivative *dS*/*dX* in order to estimate *K*.

It is now possible to calculate the theoretical *S*(*X*) and to compare it with the experimental one $\tilde{S}(X)$. However, due to the angular restriction, the integration in (6) is computed from $X_{\min}$ = -6.5 up to $X_{\max}$ = 6.5 and the experimental value of $\tilde{S}(6.5) = 4128$ is taken as an initial $S_0$. Integrals (6) result in

$$[S_1(X) - S_0]/K = \int_{(B_1-B)/2}^{(B_1+B)/2} \left\{ \int_{-\Delta/2}^{X_{\max}} I(x,y)dxdy + \int_{X}^{\Delta/2} I(x,y)dxdy \right\} \tag{7}$$

Next, introducing the function

$$J(Y,X) = \int_{(B_1-B)/2}^{(B_1+B)/2} \left\{ \int_{X}^{Y} I(x,y)dxdy \right\} \approx B(Y-X)c_0 +$$

$$B\frac{c_2}{3D^2}\left[ 2(Y^3-X^3) + (Y-X)\frac{3B_1^{\ 2}+B^2}{2} - \frac{2\frac{(Y^5-X^5)}{5} + (Y^3-X^3)\frac{(3B_1^{\ 2}+B^2)}{18} + (Y-X)\frac{(5B_1^{\ 4}+10B_1^{\ 2}B^2+B^4)}{40}}{D^2} \right]$$

$$+\frac{1}{6D}c_1\left\{ \begin{matrix} Y\left[(B_1+B)\sqrt{Y^2+(B_1+B)^2/16} - (B_1-B)\sqrt{Y^2+(B_1-B)^2/16}\right] - \\ X\left[(B_1+B)\sqrt{X^2+(B_1+B)^2/16} - (B_1-B)\sqrt{X^2+(B_1-B)^2/16}\right] \end{matrix} \right\}$$

$$+\frac{1}{6D}c_1\left\{\begin{array}{l}\dfrac{(B_1+B)^3}{32}\ln\left(\dfrac{\sqrt{Y^2+\dfrac{(B_1+B)^2}{4}}+Y}{\sqrt{Y^2+\dfrac{(B_1+B)^2}{4}}-Y}\cdot\dfrac{\sqrt{X^2+\dfrac{(B_1+B)^2}{4}}-X}{\sqrt{X^2+\dfrac{(B_1+B)^2}{4}}+X}\right)\\[2ex] +\dfrac{(B_1-B)^3}{32}\ln\left(\dfrac{\sqrt{X^2+\dfrac{(B_1-B)^2}{4}}+X}{\sqrt{X^2+\dfrac{(B_1-B)^2}{4}}-X}\cdot\dfrac{\sqrt{Y^2+\dfrac{(B_1-B)^2}{4}}-Y}{\sqrt{Y^2+\dfrac{(B_1-B)^2}{4}}+Y}\right)\end{array}\right\} \tag{8}$$

$$+\frac{1}{3D}c_1\left\{\begin{array}{l}Y^3\ln\left(\dfrac{\sqrt{Y^2+\dfrac{(B_1+B)^2}{4}}+(B_1+B)/2}{\sqrt{Y^2+\dfrac{(B_1+B)^2}{4}}-(B_1+B)/2}\cdot\dfrac{\sqrt{Y^2+\dfrac{(B_1-B)^2}{4}}-(B_1-B)/2}{\sqrt{Y^2+\dfrac{(B_1-B)^2}{4}}+(B_1-B)/2}\right)-\\[2ex] X^3\ln\left(\dfrac{\sqrt{X^2+\dfrac{(B_1+B)^2}{4}}+(B_1+B)/2}{\sqrt{X^2+\dfrac{(B_1+B)^2}{4}}-(B_1+B)/2}\cdot\dfrac{\sqrt{X^2+\dfrac{(B_1-B)^2}{4}}-(B_1-B)/2}{\sqrt{X^2+\dfrac{(B_1-B)^2}{4}}+(B_1-B)/2}\right)\end{array}\right\}$$

this relation can be rewritten as

$$\left[S_1(X)-S_0\right]/K=J(X_{\max},-\Delta/2)+J(\Delta/2,X) \tag{9}$$

and similarly

$$\left(S_2(X)-S_0\right)/K=J(X_{\max},X)+J(\Delta/2,X) \tag{10}$$

$$\left(S_3(X)-S_0\right)/K=J(X_{\max},X) \tag{11}$$

We finally can compute *K*, taking a position with $X > \Delta/2$ we obtain

$$\frac{1}{K}\frac{\delta S_3(X)}{\delta X}=B\left[c_0+2c_2\frac{X^2}{3D^2}\left(3-\frac{X^2}{D^2}\right)\right]+B\left(3B_1^2+B^2\right)\frac{c_2}{6D^2}\left(1-\frac{1}{3}\frac{X^2}{D^2}\right)$$

$$-B\left(5B_1^4+10B_1^2B^2+B^4\right)\frac{c_2}{120D^4}$$

$$+\frac{c_1}{12D}\left[\begin{array}{l}\dfrac{(B_1+B)}{2}\dfrac{32X^2+(B_1+B)^2}{\sqrt{16X^2+(B_1+B)^2}}-\dfrac{(B_1-B)}{2}\dfrac{32X^2+(B_1-B)^2}{\sqrt{16X^2+(B_1-B)^2}}\\[2ex] \dfrac{(B_1+B)^3}{\sqrt{4X^2+(B_1+B)^2}+2X}\left(\dfrac{2X}{\sqrt{4X^2+(B_1+B)^2}}+1\right)\\[2ex] -\dfrac{(B_1-B)^3}{\sqrt{4X^2+(B_1-B)^2}+2X}\left(\dfrac{2X}{\sqrt{4X^2+(B_1-B)^2}}+1\right)\end{array}\right]$$

$$+\frac{2c_1}{3D}X^2\left[\begin{array}{l} 3\ln\left(\frac{\sqrt{4X^2+\left(B_1+B\right)^2}+B_1+B}{\sqrt{4X^2+\left(B_1-B\right)^2}+B_1-B}\right) \\ +4X^2\left\{\frac{1/\sqrt{4X^2+\left(B_1+B\right)^2}}{\sqrt{4X^2+\left(B_1+B\right)^2}+B_1+B}-\frac{1/\sqrt{4X^2+\left(B_1-B\right)^2}}{\sqrt{4X^2+\left(B_1-B\right)^2}+B_1-B}\right\}\end{array}\right] \tag{12}$$

Calculating the theoretical value for, and taking the corresponding measured value from the Table 1 as $\tilde{S}_X = (4149+4111)/2 = 4130$ obtain $K$ = 2277.38. The theoretical results in comparison with the measured data are given in Fig. 5. Fig. 6 depicts the experimentally measured and theoretically predicted scale factors.

Shifting the shutter by $\delta X$ leads to a change in the signal by an amount $\delta S$. The sensor's sensitivity (spatial resolution) now can be defined as a minimal shift ($\delta X_S$) resulting in the change of the signal ($\delta S$) that is larger than the noise level ($N_S$)

$$\delta X_S : \delta S > N_S \tag{13}$$

i.e., the spatial resolution of this sensor is

$$\delta X_S > \frac{N_S}{dS/dX} \tag{14}$$

where $dS/dX$ is determined by (12).

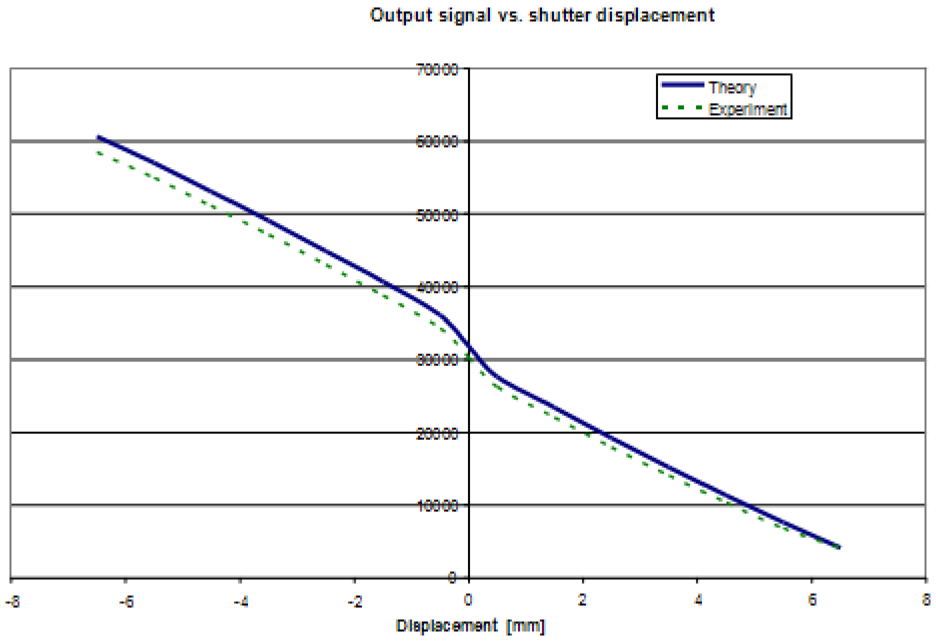


**Fig. 5.** The theoretical and experimental AOS characteristics.

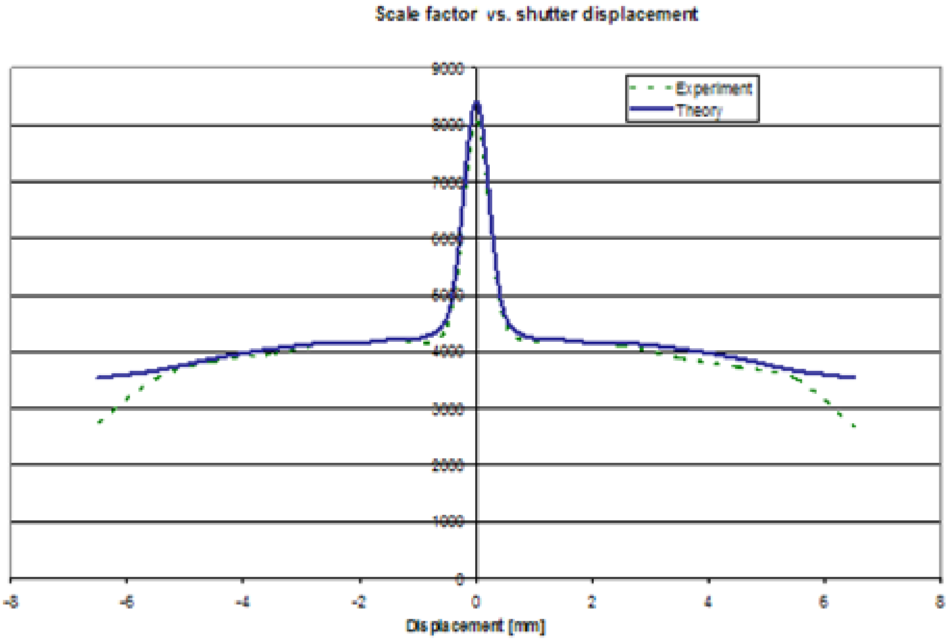


**Fig. 6.** Theoretical and experimental AOS scale factors.

## 3. Correction of the Characteristic Nonlinearity

As shown in Fig.6, the difference between experimental and calculated |*dS*/*dx*| value of the double slot sensor is not significant, i.e. the control block of the positioner may be constructed theoretically, once the AOS dimensions and elements are defined.

The structure of a positioner is given in Fig.7. It comprises a DC motor 1, connected through gear 3 to screw 5, a moving table 7 with an optical lens 10, of which the position is measured with the help of the double slot sensors 12 described above. Control block 14 determines the error between the position command and the lens position measured by the sensor and generates a control command affecting the motor through a PWM driver 15 to minimize this error. Similar structures are used in many imagers providing image zoom control.

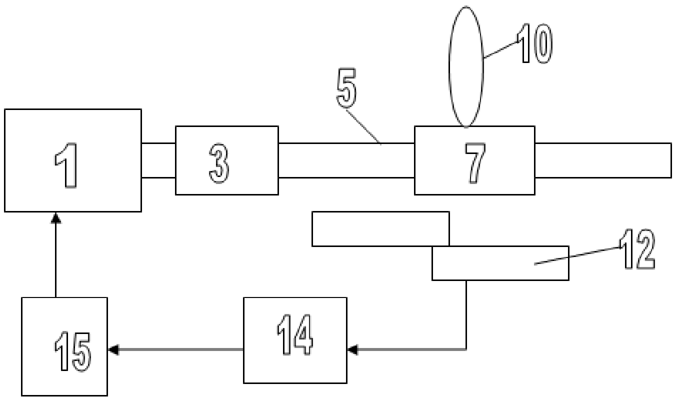


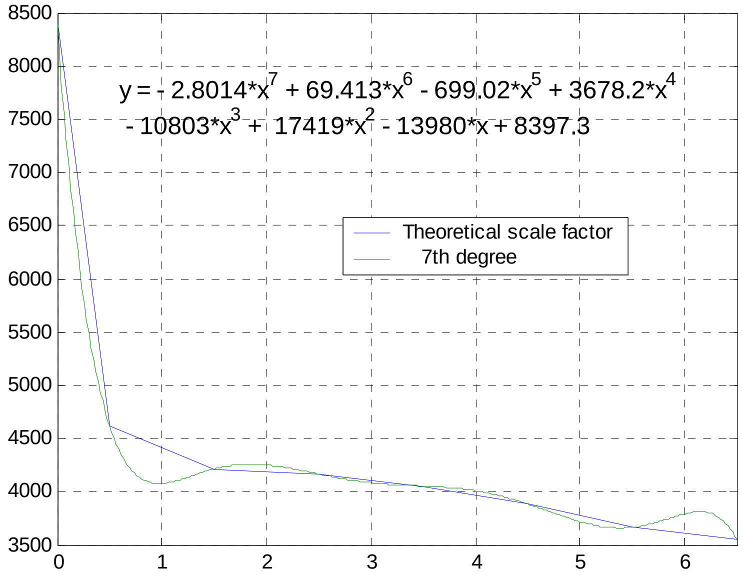
**Fig. 7.** Positioner structure.

In order to correct the nonlinearity of the system scale factor $R(X) \sim \left| dS/dX \right|$ one has to use a gain dependent on the output voltage *U*=*S*(*X*) determined by relations (8) – (11). This can be written as

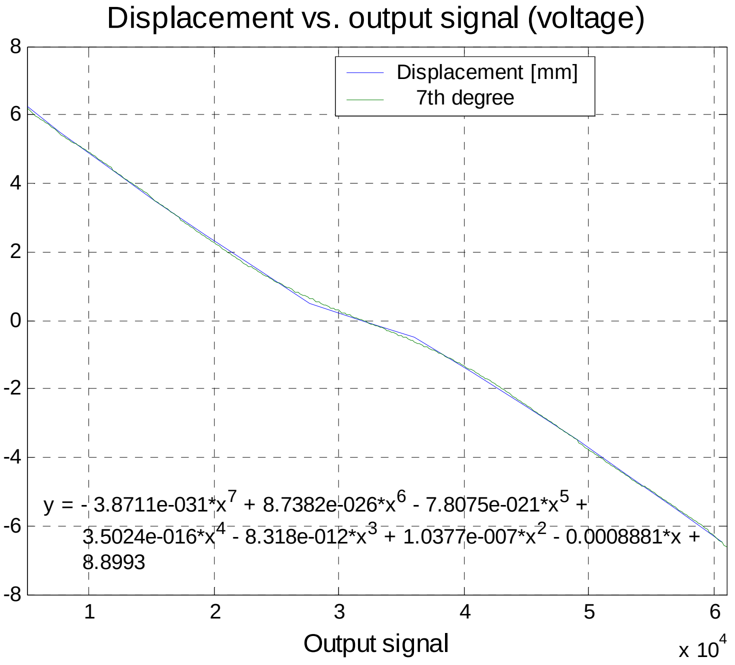
$$G(U) = R^{-1}\{S^{-1}(U)\} \tag{15}$$

As an illustration of the idea, we take a simplified model, where the theoretically calculated scale factor *R*(*X*) and the inverse output characteristics $S^{-1}(U)$ are approximated by polynomial functions (Fig. 8).

The coefficients of the proper polynomial functions were calculated using Matlab. For approximation the scale factor, only one of its symmetrical parts was used (Fig. 8a), and for implementation the relation for the whole displacement interval we use the absolute value of *X*.



(a)



(b)

**Fig. 8.** Approximation of the scale factor (a), *y* represents the scale factor and *x* is the voltage, and the inverse output characteristic (b), *y* represents the displacement and *x* is the voltage.

The resulted gain is

$$
\begin{aligned}
&G\{X(U)\} = \frac{1}{P\{X(U)\}}\\
&P(X) = -2.8014|X|^7 + 69.413|X|^6 - 699.02|X|^5 + 3678.2|X|^4 - 10803|X|^3 + 17419|X|^2\\
&-13980|X| + 8397.3\\
&X(U) = -3.8711\cdot 10^{-31}U^7 + 8.7382\cdot 10^{-26}U^6 - 7.8075\cdot 10^{-21}U^5 + 3.5024\cdot 10^{-16}U^4\\
&-8.318\cdot 10^{-12}U^3 + 1.0377\cdot 10^{-7}U^2 - 0.0008881U + 8.8993
\end{aligned}
\tag{16}
$$

and the corrected scale factor $R^{'}(X) = R(X) * G$ is shown in Fig. 9.

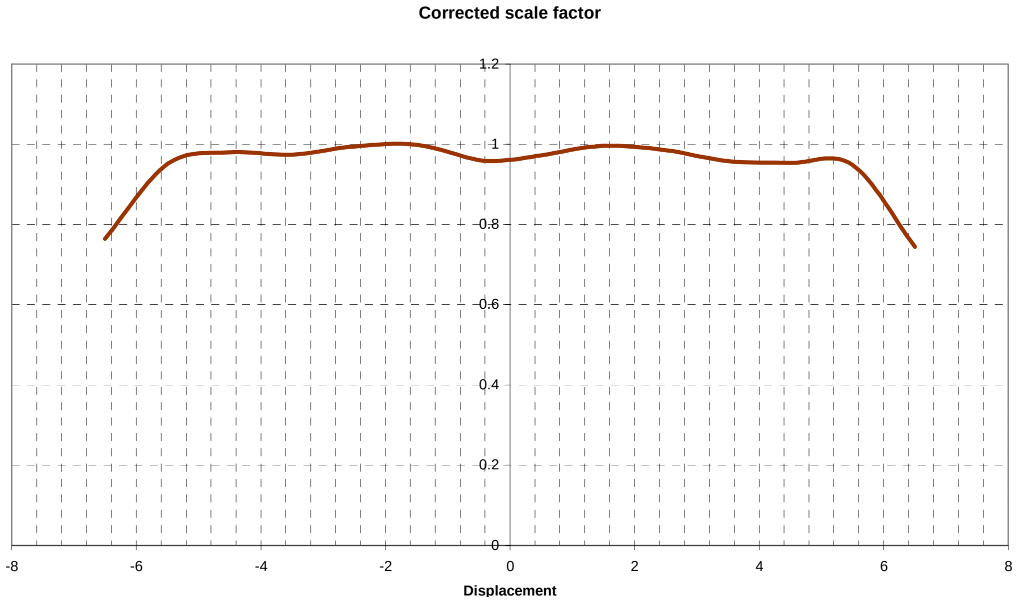


**Fig. 9.** Corrected scale factor**.**

The procedure described above is implemented by the simulation model shown in Fig. 10. It depicts the schematic model of positioner control block 14 (Fig. 7). This control block, described in Fig 10 provides practically invariant scale factor of the AOS for the positioner presented in Fig.7. It should be noted, that original AOS, having significant ratio between maximum and minimum scale factor value (more than 9dB, Fig. 6) does not provide positioner stability and accuracy at the same time in any point of its travel.

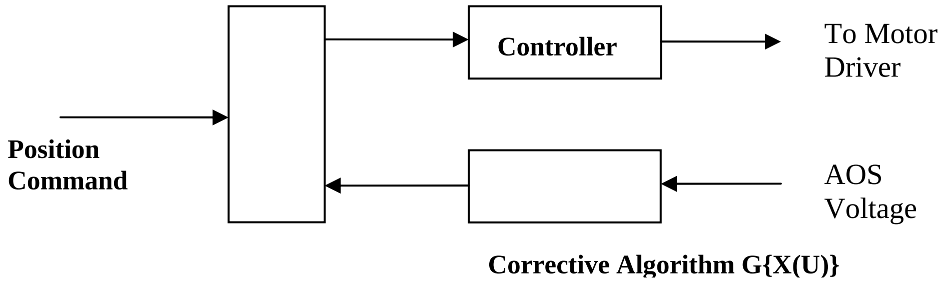


**Fig. 10.** AOS scale factor compensation in positioner control block (block 14 in Fig. 7).

## 4. Conclusions

This paper describes a method to theoretically compute the SF of an AOS, and in particular to compensate for inherent SF nonlinearities, e.g. those rising when combining multiple AOSs for extended measurement range. The main problem of AOSs with such a structure is a significant nonuniformity of the volt-displacement characteristic, appearing as a result of overlapping together with the illumination nonuniformity. This problem is fixed by using a proper corrective function, which can be *a-priori* designed on a preliminary stage based on the theoretical model developed in this paper. This correction method provides a practically constant AOS scale-factor which is necessary for a stable operating of the positioner. The volt-displacement characteristic calculated on the basis of the developed model is in a good agreement with the measured one. This successful verification allowed for creating a simulation model for positioners with increased displacement range. As an extrapolation of the present approach, a structure with several overlapped photo detectors can be suggested.

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# Guide for Contributors

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