Mechano-electric optoisolator transducer with hysteresis

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Abstract. This article presents a theoretical and experimental study of designing a mechano-electric optoisolator transducer with hysteresis. Our research is centred upon designing transducers on the basis of optical sensors, as photoelectric conversions eliminate the influence of electromagnetic disturbances. Conversion of the rotation/translation motions into electric signals is performed with the help of a LED-photoresistor Polaroid optocoupler. The driver of the optocoupler’s transmitter module is an independent current source. The signal conditioning circuit is a Schmitt trigger circuit. The device is designed to be applied in the field of automation and mechatronics.

Index Terms: Optoelectronics, Hysteresis, Polaroid optocoupler, Transducer.

1. Introduction
The applications of optoelectronics and photonics have extended far beyond the classical area of communications and have attracted a great amount of research interest from various disciplines over the last few years [1, 2]. Several areas aim at benefiting from various modalities of controlling signal output of an optocoupler by acting on the light fascicle that couples the emitter to the receiver [3-5].

Our recent work in this field has been focused on designing and testing the Polaroid optocoupler [6], which was realized by attaching Polaroid filters at the transmitter output and receiver input. As a result, the Polaroid optocoupler acts as a mechano-electric optoisolator transducer that transforms a mechanical rotational and/or translational motion into a variation of the electric signal. Since this transducer’s sensor functions on the basis of photoelectric conversions, it is not influenced by the electromagnetic disturbances in the work area.

In the field of transducers’ research, an important part is played by the study of hysteresis transducers [7, 8]. By using a Schmitt trigger (ST) circuit, the Polaroid optocoupler (PO) is transformed into a mechano-electrical optoisolator (MEO) transducer with hysteresis. Detailed analysis of it is presented in this paper along with suggested applications in the area of automation, communications and mechatronics.

2. Proposed scheme
MEO transducer with hysteresis is a device made up of the motion sensor PO, the driver of the PO’s transmitter module \( T_x \) and the signal conditioning circuit, figure 1.

Figure 1. The block diagram of the mechanical-electrical optoisolator transducer with hysteresis
The motion sensor PO uses as light source a super bright white LED. This one’s luminous intensity on the direction of the longitudinal axis is of (10,365±226) mcd, for a current of 19mA. This current’s value is kept constant by the driver of \((T_s)\) module, figure 2.

Figure 2. Circuitry of the mechanical-electrical optoisolator transducer with hysteresis

The thickness of the PO’s Polaroid filters is 0.7mm. PO’s photosensitive detector is a LDR07 photoresistor [9]. The signal conditioning circuit is a ST circuit with bipolar n-p-n BC172 transistors. This circuit is designed so as one of the two transistors is in saturation and the other one is close. The PO sensor is connected to the ST circuit by means of the resistive divisor \(R_4, P_2, R_3\). This divisor is a current-tension converter \((I, V_o)\).

3. Experimental results

The transducer’s motion sensor from figure 2 is a PO LED-photoresistor with distance adjustment. The device is in the stage of prototype [10]. POs are optocouplers at which the user has access to the optical way of the light beam coupling the transmitter \((T_x)\) module and the \((R_x)\) receiver. At the optical output of \((T_x)\) module is fixed a Polaroid polarizer filter \((P)\) and at the optical input of \((R_x)\) module is fixed a Polaroid analyzer filter \((A)\).

The optocoupler’s mechanical system is designed so that the modules can perform axial translation and rotation motions one towards the other one. The main characteristic of this new type of optocoupler consists in the possibility to modify the intensity of the electric current at the output of the photosensitive element after the processes of the light beam’s in-line polarization, re-orientation of its polarizing plan and translation motion of \((T_x)\) module towards \((R_x)\) module.

In table 1 are given the intensities of the electric current through photoresistor \(I\), for different values of \(\alpha\) angle between the polarizing plans of the two filters and distance \(d\) between \((T_x)\) and \((R_x)\) modules. These data are obtained for a supplying tension of photoresistor \(V=3\) V. By graphically representing data from table 1 are obtained the characteristics’ families: \(I=I(\alpha)_{d=\text{const}}\) and \(I=I(d)_{\alpha=\text{const}}\) from figure 3.

The transducer’s signal conditioning circuit was designed for the characteristic PO \(I=I(\alpha)_{d=93\text{mm}}\). In figure 4, is represented the transfer characteristic of the motion sensor PO \(I=I(\alpha)_{d=93\text{mm}}\) [curve(1)] and the transfer characteristic \(V_{\text{OUT}}=V_{\text{OUT}}(\alpha)_{d=93\text{mm}}\) of the MEO transducer with hysteresis [curve (2)].

That device is a transducer with inverting hysteresis. Whenever the dihedral angle goes over the High Threshold Level \(\alpha_H \approx 74^\circ\) (when the output current of the PO sensor \(I_L=14\mu\)A), the output of the transducer is switched LOW \((V_{\text{OUT,L}}=1.63V)\). The output will remain in this state, as long as the dihedral angle is above the Low Threshold Level \(\alpha_L \approx 19^\circ\), when the output current of the PO sensor \(I_H=71\mu\)A. When the dihedral angle goes below this level, the output of the ST circuit will switch \((V_{\text{OUT,H}} \approx 11.5V)\).
**Table 1.** The output current intensities of the LED–photoresistor MEO transducer expressed in (µA), for different values of $\alpha$ and $d$

| Angle (DEG) | Distance (mm) | 78 | 83 | 88 | 93 | 98 | 103 | 108 | 113 |
|-------------|---------------|----|----|----|----|----|------|------|-----|
| 0           | 105           | 95 | 87 | 78 | 71 | 65 | 60   | 56   |
| 10          | 102           | 93 | 84 | 75 | 70 | 64 | 59   | 54   |
| 20          | 95            | 85 | 77 | 70 | 65 | 58 | 54   | 50   |
| 30          | 85            | 75 | 67 | 60 | 56 | 51 | 47   | 44   |
| 40          | 70            | 63 | 55 | 51 | 46 | 42 | 39   | 37   |
| 50          | 54            | 47 | 43 | 40 | 36 | 33 | 31   | 29   |
| 60          | 35            | 32 | 30 | 27 | 25 | 23 | 21   | 19   |
| 70          | 22            | 19 | 18 | 17 | 15 | 14 | 12   | 12   |
| 80          | 12            | 10 | 10 | 9  | 8  | 7  | 7    | 6    |
| 90          | 7.2           | 6.5 | 5.9 | 5.3 | 4.9 | 4.5 | 4.1 | 3.8 |

**Figure 3.** The characteristics’ family of the LED–photoresistor MEO sensors: a) $I=I(\alpha), d=\text{const.}$ and b) $I=I(d), \alpha=\text{const}$.

**Figure 4.** The response characteristics of the PO sensor (1); The response characteristics of the MEO transducer with hysteresis (2).
4. Theoretical analysis of the device

If the intensity of the current through the LED in figure 5 is maintained constant, then the luminous intensity of the source \( I \) is constant in time. This radiation will produce a luminous illumination \( E_{vP} \) on the surface of a Polaroid polarizer filter which is at distance \( d_P \) from the LED.

\[
E_{vP} = \frac{J_v}{d_P^2} \tag{1}
\]

**Figure 5.** a) LED–photoresistor MEO transducer; b) Polarized LED–photoresistor MEO transducer

Equation (1) is true if the detector diameter is at least ten times smaller than the LED-photoresistor distance \( d \) – ‘the rule of ten diameters’ - and the light beam falls perpendicular to the detector surface. Knowing that the radiation’s luminous illumination \( E_v \) and luminous exitance \( M_v \) are proportional with the square of the maximum value of the electrical field’s intensity, according to Malus’s law, one can show that radiation luminous exitance \( M_{vP} \) at the exit of the filter \( P \) is given by the following relation:

\[
M_{vP} = \frac{E_{vP}}{2} = \frac{J_v}{2 \cdot d_P^2} = \frac{J_{vP}}{d_P^2} \tag{2}
\]

Equation (2) considers ideal Polaroid filters (i.e. the transmission coefficient in the transmission axis is \( T'=1 \), the reflection coefficient is \( R'=0 \) and the absorption coefficient in the orthogonal axis is \( A'=1 \) and in any other situation, their values are: \( T=0, A=0, R=0 \)). From relation (2) and figure 5 can be noticed that the system formed by a LED with luminous intensity \( J_v \) and the Polaroid filter \( P \) is equivalent with a polarized LED with luminous intensity \( J_{vP} \) [11].

In this case, according to Malus’s law, the luminous illumination at the input of the Polaroid filter \((A)\ E_{vA}\) the luminous exitance at the output from the Polaroid filter \( (A)\ M_{vA}\) and the luminous illumination of the surface of the photoresistor \( E \), are given by the relations:

\[
E_{vA} = \frac{J_{vP}}{d_A^2}; \quad M_{vA} = E_{vA} \cdot \cos^2 \alpha = \frac{J_{vP}}{2 \cdot d_A^2} \cdot \cos^2 \alpha; \quad E_v = \frac{J_v}{2 \cdot d^2} \cdot \cos^2 \alpha \tag{3}
\]

where \( d_A \) is the distance LED-Polaroid filter \( A \) and \( d \) is the LED-photoresistor distance.

When the photosensitive surface of the photoresistor from figure 2 is illuminated, through it passes a photocurrent given by the expression:

\[
I = I_d + C_1 \cdot E_v^a = I_d + C_1 \left( \frac{J_v}{2 \cdot d^2} \cdot \cos^2 \alpha \right)^a \approx C \cdot \frac{\cos^2 \alpha}{d^2 a} \tag{4}
\]
where: \( C = C_1 \cdot (J_v / 2)^a \), \( I_d \) is the darkness current which is actually negligible as compared to photocurrent in the case of LDR07 photoresistor, \( a \) is a parameter depending on the level of the photoresistor’s illumination and \( C_1 \) is a proportionality constant. It depends on the voltage \( V \) applied to the photoresistor, on the radiation frequency and the photoresistor type.

This photocurrent appears because of the photoconductivity’s dependence on illumination.

Since when \( \alpha = 90^\circ \), the transmission coefficient in the transmission axis of real polarizer filter \( T \neq 0 \) (figure 3), an additional parameter \( T \) must be introduced in (4):

\[
I(\alpha, d) = C \cdot \frac{\cos^2 \alpha + T}{d^{2a}}
\]

Equation (5) represents the theoretical transfer characteristics’ family \( I = I(\alpha, d) \), for LED-photoresistor PO sensor. So as PO sensor can command the ST circuit, photocurrent \( I \) must be converted into the command tension \( V_A \).

The transfer function of the current-to-voltage converter from figure 2 can be expressed as follows:

\[
V_A(I) = \frac{V_{CC} \cdot (R_{P_2} + R_4) + I \cdot R_4 \cdot R_3}{R_3 + R_{P_2} + R_4}
\]

(6)

From (5) and (6) is obtained the dependence function of the command voltage \( V_A \) of ST circuit’s on \( \alpha \) angle.

\[
V_A(\alpha) = \frac{V_{CC} \cdot (R_{P_2} + R_4) \cdot d^{2a} + C \cdot R_4 \cdot R_3 \cdot \cos^2 \alpha + T}{(R_3 + R_{P_2} + R_4) \cdot d^{2a}}
\]

(7)

If \( R_{P_2} = R_{P_3} = 0 \), the high trigger voltage \( V_{AH} \) and the low trigger voltage \( V_{AL} \) can be approximately calculated as:

\[
V_{AH} = \frac{V_{CC} \cdot R_8}{R_5 + R_6 + R_8} + V_{BE\text{SAT}} \approx \frac{V_{CC} \cdot R_8}{R_5 + R_6 + R_8} - 0.15 \pm 1.39\,V \]

(8)

\[
V_{AL} = V_{BE\text{SAT}} + \frac{V_{CC} \cdot R_8}{R_5 + R_6 + R_8} - V_{BE\text{ON}} \approx \frac{R_3 \cdot R_8}{R_5 \cdot R_6 + R_8 + R_7} + 1.21\,V
\]

(9)

where: \( V_{BE\text{SAT}} \approx 0.7\,V \) is the base emitter saturation voltage and \( V_{BE\text{ON}} \approx 0.55\,V \) is the base emitter opening voltage [12].

5. Results. Discussion

I for the extreme cases \( \alpha = 0^\circ \) and \( \alpha = 90^\circ \) when \( d = 93\,mm \), the values for the empirical constants \( T \) and \( C \) are obtained. Constants \( a \) are determined by superposing the characteristics given by (5) over the experimental characteristics from figure 3a. As a result, the theoretical transfer characteristic (10) for our prototype is as it follows:

\[
I(\alpha, d) = 193.44\,mA \cdot (mm)^{1.74} \cdot \frac{\cos^{1.74} \alpha + 0.073}{d^{1.74}}
\]

(10)

In this case (7) becomes:
In figure 6 are rendered two-dimensional graphic representations $I=I(\alpha)d=\text{const.}$ and $I=I(d)\alpha=\text{const.}$ of (10).

By replacing in (11) the dihedrals angle Threshold Level $\alpha_H \cong 74^\circ$ and $\alpha_L \cong 19^\circ$, the theoretical value of the voltage threshold level are obtained to change the state ST circuit: $V_{AH} \cong 1.39V \ (8)$ and $V_{AL} \cong 1.21V \ (9)$. These values have been calculated for a distance between ($T_x$) and ($R_x$), modules of $d=93\text{mm}$.

If in the circuit in figure 2, $R_{P1} \neq 0$ and $R_{P2} \neq 0$, the voltage threshold level $V_{AH}$ and $V_{AL}$ can be modified as:
They can also be adjusted by modifying resistance $R_{p2}$ (11).

The modification of the voltage threshold level $V_{AH}$ and $V_{AL}$ permits the adjustment by means of the electrical way of the dihedral angle threshold Level $\alpha_H$ and $\alpha_L$.

From Figure 8 can be noticed that the adjustment of the dihedral angle’s threshold level $\alpha_H$ and $\alpha_L$ can be achieved through optical way, too.

$$V'_{AH} = V_{AH} \left( \frac{R_7 + R_{p2}}{R_7} \right) - V_{BE{\text{on}}} \frac{R_7}{R_7}$$  \hspace{1cm} (12)

$$V'_{AL} = V_{AL} \left( \frac{R_7 + R_{p2}}{R_7} \right) - V_{BE{\text{on}}} \frac{R_7}{R_7}$$  \hspace{1cm} (13)

Figure 8. Mechno-optical adjustment of the dihedral angle’s threshold level $\alpha_H$ and $\alpha_L$.

The increase in angle threshold level $\alpha_H$ and the decrease in angle threshold level $\alpha_L$ can be achieved by increasing distance $d$ between ($T_x$) and ($R_x$) modules.

So as the voltage threshold level $V_{OUTL}$ can be low, transistor $T_1$ must be in saturation state and the value of $R_7$ must be low. If applications in which this transistor is used need that the voltage threshold level $V_{OUT}$ to be low and the circuit’s commutation to be rapid, $T_2$ and $T_3$ transistors must be Schottky transistors. These rapid transistors, fitted with Schottky limiting diodes between collector and base, allow the transistor to be wide opened without being deeply in saturation. In this case, the transistor’s much lower switching time ($t_{ON}$ and $t_{OFF}$), determine the increase of the work speed [13].

The modification of the distance between ($T_x$) and ($R_x$) can be also used to compensate in time the effects appearing as a consequence of the LED’s ageing.

The applications’ domain in which this new type can be used is much diversified.

If it is used as detector of the circuit voltage’s presence figure 9, as compared to the classical optocouplers detectors, this device allows the mechno-optical adjustment of the level of detecting the circuit voltage which must be detected, as well as the domain of the voltages in which this one can fluctuate.
The adjustment of the nominal work voltage level is performed by modifying the Polaroid optocoupler’s $\alpha$ parameter, and the settlement of the domain in which the circuit voltage can fluctuate is made by modifying parameter $d$, figure 8.

Mechano-optical adjustments allowed by this device offer it advantages as compared to classical optocouplers and also in the case when these ones are used for filtering digital signals accompanied by noise. If this transducer is used as tachometer, it isn’t influenced by electromagnetic disturbances, and the modification of parameter $d$ allows the modulation in width of the impulses formed by the device.

If $\alpha$ parameter is modified only in the interval $(0^\circ–90^\circ)$, the transducer can be used for the automatic measurement of the water level in a dam, figure 10 [14]. The possibility to modify parameter $d$ allows the transducer’s re-calibration in time.

6. Conclusions
The transducer proposed by us, using a Polaroid optocoupler sensor is not affected by electromagnetic disturbance. This characteristic advantages it when using it in areas with electromagnetic disturbances.

The use as a circuit conditioning a ST circuit, allowed the obtaining of a memory mechano-electric transducer. This characteristic determines its use in the applications where one needs the memorization of the machine-tools’ extreme positions during motion.

The optocoupler’s remote adjustment offers the advantage of its optimization or re-calibration by the mechano-optical way. This adjustment, unlike the electric adjustment (12, 13), doesn’t depend on temperature.

The device designed by us is meant to be applied in the field of automation and mechatronics.

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