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Research paper

Parameters determination and error compensation for low-cost piezoresistive sensor measurements

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Abstract

A calibration algorithm of pressure sensor for estimation of parameters and error compensation is presented in this paper. Voltage values corresponding to temperatures and pressures are measured to obtain the seven parameters for four calibration equations. Calculation of the calibration coefficients is done in the LabView environment, and these seven coefficients are stored inside a 16-bit microcontroller non-volatile data memory. For low-cost implementation, the pressure values are processed within the program memory with the size of only 8kB. As a result, the measurement of voltages from pressure and temperature sensors via the microcontroller can be executed and transmitted back to LabView.

Keywords: *Calibration; Microcontroller; Numerical Approximation; Piezoresistive Sensor.*

1. Introduction

Today's market offers a wide range of pressure sensors for system design. Some sensors provided by the manufacturers are compensated with integrated circuitry, while others are strictly sensors without any compensation. Silicon piezoresistive pressure sensors have been used in applications such as water level measurement in a washing machine, blood pressure measurement, or altitude measurement. Such pressure sensors are cheap and equipped with a built-in temperature sensor. Regardless how sophisticated pressure sensors have been manufactured nowadays, these sensors have something in common: they suffer from offset, non-linearity and temperature dependence. Therefore, the output of the sensor is not an accurate and reliable representation of the measured physical quantity. Hence many researches have been done to obtain suitable calibration methods [1-7]. A calibration system based on iterative method, where the calibration coefficient is determined from a set of functions at selected points to calculate the first correction of the transfer curve until it developed into a polynomial transfer correction, has been developed in [1]. A curve-fitting algorithm based on cubic B-spline is developed in [8] for accuracy and efficiency. Another method is by providing linearization function in the interface circuit for a capacitive sensor, where the implementation is done by using a switched-capacitor charge balancing analog-to-digital converter (ADC) [3].

In this paper, an algorithm for low-cost silicon piezoresistive relative pressure sensor is presented. The scope of the algorithm development only deals with the pressure sensor calibration and not the temperature sensor. The temperature sensor is assumed to produce the value of the actual temperature. The measured voltage from the temperature sensor is converted into temperature using the developed algorithm. The desired result of calibration will compensate the offset, and the measured deviation should be 0.5% of the maximum pressure for normal temperatures (0°C – 80°C), and 1% for extreme temperatures (i.e. less than 0°C and above 80°C), as shown in Fig. 1.

This paper is organized by describing and deriving the proposed algorithm in Section 2. Section 3 describes the methodology of the algorithm development. Section 4 presents the results and discussions on the measurements of the sensors and its improvement, and the last section is the conclusion of the research.

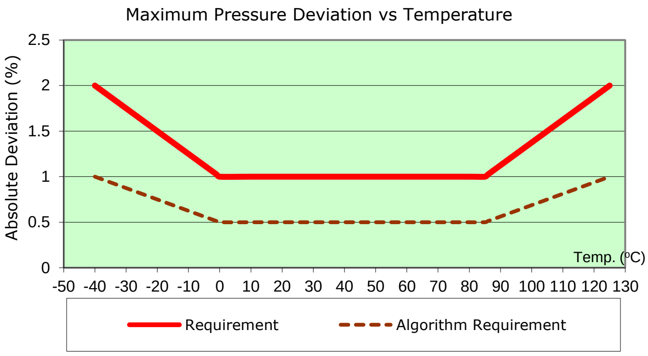

Fig. 1: Requirement of Pressure Deviation.

2. Principle description

The pressure sensor is calibrated by using quadratic approximation given by the expression [9]:

$$P(V) = AV^2 + BV + P_0 \qquad (1)$$

Equation (1) represents the general behaviour of the sensor. Since inside the pressure chamber consists of pressure and temperature sensors, the sensor actually measures voltage (V) for the corresponding pressure (P) at temperature (θ). The approximated coefficients (A and B) are also defined with temperature function. During calibration process, two things are needed to be implemented: to modify the equation so that it will be a function of voltage only (not with pressure offset P_0, but instead with voltage offset V_0 at zero pressure), and to represent all the voltage coefficients (including voltage offset V_0) in terms of temperature function. The linear relation of P as a function of V will be determined. The linear relation can be written as (2). Differentiating this equation yields (3) where m is the sensitivity.

$$P(V) = mV + P_0 \quad (1)$$

$$\frac{dP(V)}{dV} = m \quad (2)$$

Rearranging $P(V) = mV + P_0$ (1) yields:

$$V = \frac{1}{m}P + V_0 \quad (3)$$

$$\therefore P_0 = -mV_0 \quad (4)$$

Equation $\therefore P_0 = -mV_0$ (4) provides the relation between P_0 and V_0. This relation is used in the quadratic approximation of the pressure sensor. Equation $\frac{dP(V)}{dV} = m$ (2) can also be defined as:

$$\frac{dP(V)}{dV} = m = 2AV + B \quad (5)$$

Equation $\frac{dP(V)}{dV} = m = 2AV + B$ (5) is substituted into $\therefore P_0 = -mV_0$ (4) to get an equation of P_0 in terms of V_0. Hence,

$$P_0 = -\left(\frac{dP(V)}{dV}\right)\cdot V_0 = -mV_0 = -(2AV + B)\cdot V_0 \quad (6)$$

Equation **Error! Reference source not found.**) can be re-written as:

$$P(V) = AV(V - 2V_0) + B(V - V_0) \quad (7)$$

Coefficients A and B are approximated by linear temperature function, and V_0 performs quite well with quadratic approximation with temperature.

a) Coefficient A

$$A = a_1\theta + a_0 \quad (8)$$

b) Coefficient B

$$B = b_1\theta + b_0 \quad (9)$$

c) Offset

$$V_0 = c_2\theta^2 + c_1\theta + c_0 \quad (10)$$

Because the pressure is now in term of quadratic approximation, the sensitivity, m, as stated in $P_0 = -\left(\frac{dP(V)}{dV}\right)\cdot V_0 = -mV_0 = -(2AV + B)\cdot V_0$ (6), is then as a function of measured voltage V. Therefore, A and B can be solved by finding two points of m at two distinct voltages.

$$\begin{pmatrix} m_1 \\ m_2 \end{pmatrix} = \begin{pmatrix} V_1 & 1 \\ V_2 & 1 \end{pmatrix}\begin{pmatrix} 2A \\ B \end{pmatrix} \quad (11)$$

$$\underline{m} = \underline{\underline{V}} \cdot \underline{G} \quad (12)$$

In quadratic curve, the determination of sensitivity at V_1 requires three points: two points for the tangent (gradient) and another point in the middle for the sensitivity. In other words, finding the values of m_1 and m_2 requires six points. On the other hand, the number of points can be reduced by overlapping the determination of m_1 and m_2. This idea is depicted in Fig. 2.

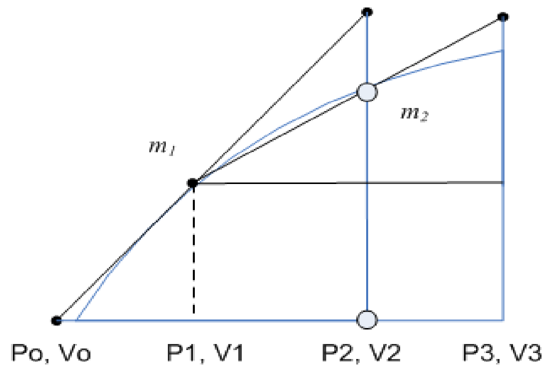

Fig. 2: Determination of Sensitivity.

2.1. First case: coefficients of a and b as linear temperature function

Four pressure points are needed to approximate A and B at a constant temperature θ_1. The evaluation of m_1 and m_2 are given as:

$$m_1 = \frac{\Delta P}{\Delta V} = \frac{P_0 - P_2}{V_0 - V_2} \quad (13)$$

With V_1 is the voltage at pressure P_1 (middle pressure between P_0 and P_2) at $\theta=\theta_1$; and

$$m_2 = \frac{\Delta P}{\Delta V} = \frac{P_1 - P_3}{V_1 - V_3} \quad (14)$$

With V_2 is the voltage at pressure P_2 (middle pressure between P_1 and P_3) also at $\theta=\theta_1$. The values of m_1 and m_2 in matrix form is used to solve for both A and B simultaneously. The cap '^' represents an approximation. Equations $\begin{pmatrix} m_1 \\ m_2 \end{pmatrix} = \begin{pmatrix} V_1 & 1 \\ V_2 & 1 \end{pmatrix}\begin{pmatrix} 2A \\ B \end{pmatrix}$ (11) and $\underline{m} = \underline{\underline{V}} \cdot \underline{G}$ (12) can be written as:

$$\begin{pmatrix} m_1 \\ m_2 \end{pmatrix} = \begin{pmatrix} V_1 & 1 \\ V_2 & 1 \end{pmatrix}\begin{pmatrix} 2A_1 \\ B_1 \end{pmatrix} \quad (15)$$

$$\underline{m} = \underline{\underline{V}} \cdot \underline{G_1} \quad (16)$$

$$\underline{\hat{G}_1} = \underline{\underline{V}}^{-1} \cdot \underline{m} \text{ at } \theta=\theta_1 \quad (17)$$

The same method applies for $\theta=\theta_2$.

$$\begin{pmatrix} m_1 \\ m_2 \end{pmatrix} = \begin{pmatrix} V_1 & 1 \\ V_2 & 1 \end{pmatrix}\begin{pmatrix} 2A_2 \\ B_2 \end{pmatrix} \quad (18)$$

$$\underline{m} = \underline{\underline{V}} \cdot \underline{G}_2 \quad (19)$$

$$\underline{\hat{G}}_2 = \underline{\underline{V}}^{-1} \cdot \underline{m} \text{ at } \theta=\theta_2. \quad (20)$$

Based on (17) and (20), the linear coefficient for both A and B (a_1, a_0, b_1 and b_0) can be written as:

$$\begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = \begin{pmatrix} \theta_1 & 1 \\ \theta_2 & 1 \end{pmatrix} \begin{pmatrix} a_1 \\ a_0 \end{pmatrix} \quad (21)$$

$$\underline{A} = \underline{\underline{\theta}} \cdot \underline{a} \quad (22)$$

Therefore,

$$\underline{\hat{a}} = \underline{\underline{\theta}}^{-1} \cdot \underline{A} \quad (23)$$

Where $\underline{\hat{a}}$ is the coefficient approximation. Similarly,

$$\begin{pmatrix} B_1 \\ B_2 \end{pmatrix} = \begin{pmatrix} \theta_1 & 1 \\ \theta_2 & 1 \end{pmatrix} \begin{pmatrix} b_1 \\ b_0 \end{pmatrix} \quad (24)$$

$$\underline{B} = \underline{\underline{\theta}} \cdot \underline{b} \quad (25)$$

Therefore,

$$\underline{\hat{b}} = \underline{\underline{\theta}}^{-1} \cdot \underline{B} \quad (26)$$

Where $\underline{\hat{b}}$ is the coefficient approximation.

2.2. Second case: coefficients of v0 as quadratic temperature function

The offset voltage is a function of temperatureθ, which is defined as $V_0 = c_2\theta^2 + c_1\theta + c_0$. To evaluate the coefficients of the offset voltage V_0 (i.e. c_2, c_1 and c_0), three offset voltages are required (measures at 0 Bar for three different temperature values θ_1, θ_2 and θ_3). Written in matrix form:

$$\begin{pmatrix} V_{01} \\ V_{02} \\ V_{03} \end{pmatrix} = \begin{pmatrix} \theta_1^2 & \theta_1 & 1 \\ \theta_2^2 & \theta_2 & 1 \\ \theta_3^2 & \theta_3 & 1 \end{pmatrix} \begin{pmatrix} c_2 \\ c_1 \\ c_0 \end{pmatrix} \quad (27)$$

$$\underline{V}_0 = \underline{\underline{\theta}} \cdot \underline{c} \quad (28)$$

$$\underline{\hat{c}} = \underline{\underline{\theta}}^{-1} \cdot \underline{V}_0 \quad (29)$$

Where $\underline{\hat{c}}$ is the coefficient approximation. Hence, three temperature points are required, i.e. at each temperature, three offset voltages are measured – each at 0 Bar. With this, a 3-by-3 matrix is formed forθ, and a 3-by-1 vector for V_0. The overall calculated coefficients presented above are simplified into

$$\hat{P} = \hat{A}V\left(V - 2\hat{V}_0\right) + \hat{B}\left(V - \hat{V}_0\right) \quad (30),$$

which is the pressure calibration approximation.

$$\hat{P} = \hat{A}V\left(V - 2\hat{V}_0\right) + \hat{B}\left(V - \hat{V}_0\right) \quad (30)$$

The algorithm is improved further by approximating the offset with 3rd order polynomial at lower temperature by using approximated quadratic polynomial and general constant. So, the improved algorithm (for offset only) will be:

$$\hat{V}_0 = \hat{c}_3\theta^3 + \hat{c}_2\theta^2 + \hat{c}_1\theta + \hat{c}_0 = (\hat{c}_2\theta^2 + \hat{c}_1\theta + \hat{c}_0)(k_1\theta + k_0) \quad (31)$$

For $\theta < \theta_C$ where θ_C is defined as critical temperature, and for $\theta \geq \theta_C$:

$$\hat{V}_0 = \hat{c}_2\theta^2 + \hat{c}_1\theta + \hat{c}_0 \quad (32)$$

3. Methodology

The developed algorithm is strongly based on the data study of now-obsolete KP202R pressure sensor by Infineon [10]. The specification of measurement is for the pressure range of -0.6 bar to +0.6 bar with the accuracy of the span of about 0.5% of the final value of 0.6 bar with the overall temperature range accuracy of 2%.The algorithm development and measurement workflow can be shown in Fig. 3.

The selection of temperature points should count on solving for all coefficients for A, B and V_0. Since V_0 is a polynomial approximation, it requires three temperature points. Meanwhile, A, and B are linear approximations and they require two temperature values (20ºC and 50ºC). Temperature below 20ºC can easily be achieved by water-cooling. Based on the KP202R datasheet, the selected temperature points are θ_1 = 20°C, θ_2 = 50°C, θ_3 = 85°C. The selection of pressure points is full range (from 0 Bar to 0.6 Bar). The measure of voltages at 0 Bar is necessary to find the offset value, and at 0.6 Bar to find the final desired value. The selected pressure points are P_0 = 0 Bar, P_1 = 0.2 Bar, P_2 = 0.4 Bar, P_3 = 0.6 Bar.

Due to the lack of space, the values of k_1 and k_0 in (32) are determined statistically from available sensors. (V_0 are approximated using Least Square fit for all sensors. The median value is taken from the result). These values are k_1 = -0.0051, k_0=1.0341 and θ_C=-20ºC.

3.1. Units of voltage, temperature and pressure for integer arithmetic

A C program is developed to handle the linearization algorithm and communications between microcontroller and computer using serial UART interface. Configuring of the ADC within microcontroller is used for converting the analog measured voltages from external device for linearization calculation algorithm.

To fit the algorithm into an 8kB of memory, integer arithmetic is implemented in the software. Using floating point arithmetic would increase the size of the code and will be too large to fit in the microcontroller memory. Thus, converting the small floating coefficient value into one accurate integer can be employed.

Due to the required precision of the linearization algorithm, a microcontroller with at least 16 bits is chosen for this application [11]. The units for ADC 16-bit resolution are determined such that maximum values of the physical quantities voltage V, pressure P and temperature have an order of magnitude in the range from 2^{14} = 16384 to 2^{16} = 65536, if the physical quantity is unipolar (e.g. voltage and temperature in ºC). If the physical quantity (e.g. pressure) is bipolar the limits should be reduced by a factor of two. For integer calculations, the units are shown in Table 1.

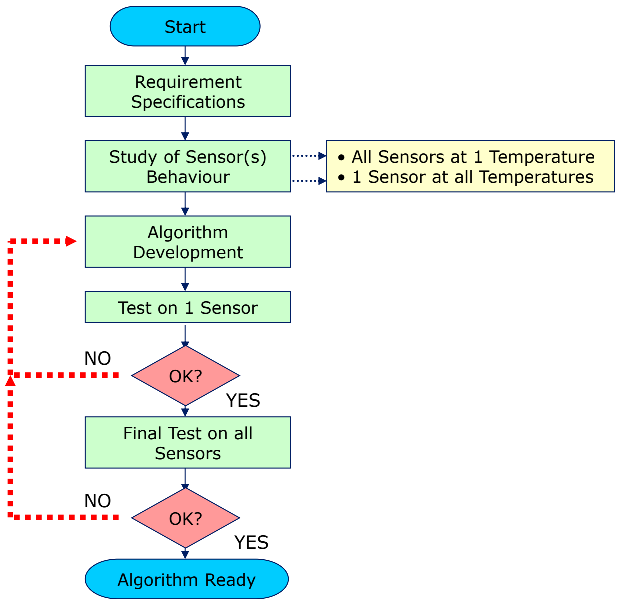

Fig. 3: Algorithm and Measurement Workflow.

Table 1: Unit Definitions for Integer Arithmetic Calculation

Unit of Pressure:	1 UoP = 0.02 mBar
Unit of Temperature:	1 UoT = 0.01ºC
Unit of Voltage:	1 UoV_p = 5µV for pressure measurement 1 UoV_T = 50µV for temperature measurement

For the pressure values between -0.6 bar to +0.6 bar, the unit of pressure (UoP) used in the software is

$$\frac{0.6bar}{32768} = 0.0183mbar \approx 0.02mbar$$

The range of input voltages is best fit by an ADC with input range of ± 160mV at a reference voltage of 2.5V. For UoV_P, one least-significant bit (LSB) of the ADC is equal to

$$\frac{160mV}{32768} = 4.88\mu V \approx 5\mu V$$

The same procedure is used for calculation of UoT and UoV_T. These units are employed to convert the pressure and temperature approximation function into integer arithmetic calculation. The program assigns the coefficients mentioned in previous section as a signed long integer value. These values are converted within Labview software. The actual value can be obtained by rounding up the accurate value by dividing its span, depending on the size of its mantissa.

3.2. Calibration system

Fig. 4 shows the calibration system of the pressure transducer. The system consists of a computer (PC) with a GPIB interface card for controlling the devices. The LabView software by National Instruments is used for visualization i.e. GUI, and control of the calibration procedure. The pressure controller, which is DPI 510 from Druck Messtechnik GmbH, will provide the relative pressure to the sensor, while the sensor will permit measurements to be done in different temperatures. The verification of the temperature measurement is compared with the results obtained from a temperature test System VT4004 from Vötsch Industrietechnik GmbH.

The LabView environment will determine the calibration coefficients. These values are then stored into the microcontroller non-volatile data memory. The approximation equations will be executed inside the program memory. Here, the microcontroller is able to read the measured voltages from both sensors (i.e. pressure and temperature) based on the stored coefficients, and perform the calculation and return the values to LabVIEW. Fig. 5 shows the developed hardware of the microcontroller circuit.

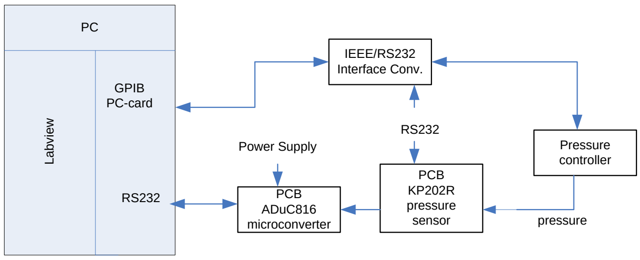

Fig. 4: Block Diagram of the Calibration System.

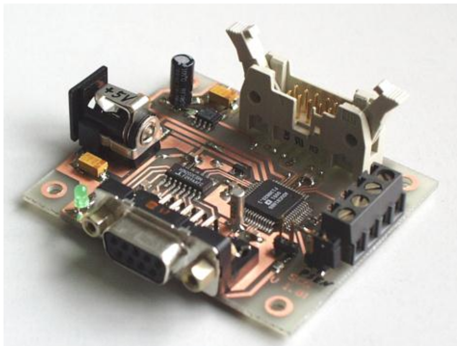

Fig. 5: Developed Circuit of the Sensor and Microcontroller.

4. Results and discussions

The developed algorithm was tested on forty sensors. The selected temperature, pressure points and corresponding voltage values are given in Table 2. The deviation result from proposed algorithm is shown in Table 3. Based on the results for the normal temperature range (0ºC to 100ºC), all sensors perform very well with very small deviation. The deviation percentages between the required and measured results are shown in Fig. 6. As can be observed, the developed algorithm produced a more improved deviation values compared to the required specification. The deviation is less than or equal to 0.5% for normal temperature range and also at extreme temperatures. However, the deviation increases more than 0.5% after -25ºC.

Table 2: Selected Temperatures and Pressure Points

Pressure Temp.	0.0 Bar	0.2 Bar	0.4 Bar	0.6 Bar
19.5 ºC	-1.876521 V	39.199916 V	80.683337 V	122.650210 V
50.1 ºC	-1.003907 V	37.266833 V	76.068576 V	115.256660 V
81.8 ºC	-0.708101 V	35.122825 V	71.556247 V	108.365470 V

Table 3: Voltage Deviations of Proposed Algorithm for One Sensor

Pressure Temp.	0.0 Bar	0.1 Bar	0.2 Bar	0.3 Bar	0.4 Bar	0.5 Bar	0.6 Bar
-20.0ºC	0.000302	0.000923	0.000647	0.000015	-0.000587	-0.000868	-0.000861
19.5ºC	-0.000002	-0.000119	0.000028	0.000126	0.000212	0.000288	0.000249
50.1ºC	-0.000001	0.000149	0.000285	0.000267	0.000153	0.000228	0.000432
81.8ºC	0.000000	0.000144	-0.000001	-0.000385	-0.000847	-0.001128	-0.001187
102.0ºC	0.000396	0.000345	-0.000107	-0.000645	-0.001359	-0.001856	-0.002013

Fig. 7 and Fig. 8 show the results before and after calibration with the algorithm of one sensor. The result shows that the algorithm has a margin of tolerance for additional errors that might occur during measurement and calculation. However, only two out of forty sensors have the result that is 0.5% outside of the proposed deviation at extreme temperatures.

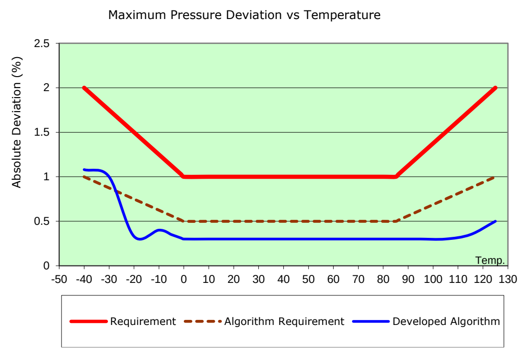

Fig. 6: Comparison of the Deviation between the Requirement, Algorithm Requirement and the Developed Results for A Range on Temperature (-40ºc to 125ºc).

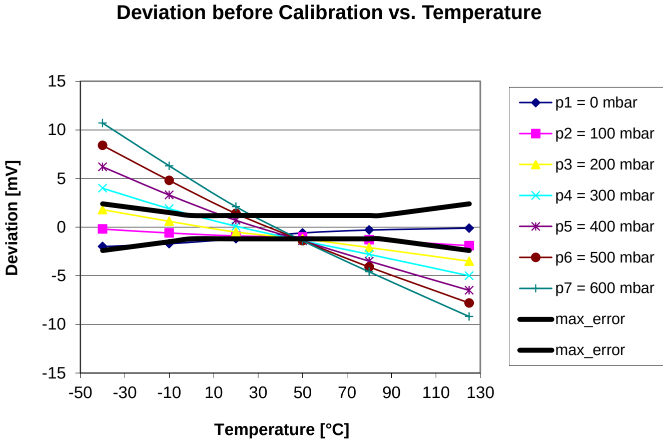

Fig. 7: Deviation before Calibration at Fixed Pressure.

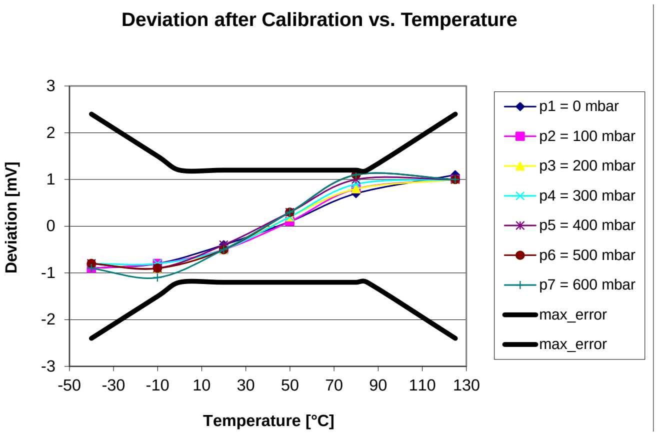

Fig. 8: Deviation after Calibration at Fixed Pressure.

5. Conclusion

An algorithm of four calibration equations with seven coefficients has been developed with satisfying results. The algorithm is done in integer arithmetic to fit the size of the code into an 8kB memory. When the microcontroller measures the voltage for corresponding pressure, it will approximate the calibrated pressure by using this algorithm, and send the calculated value to the PC (LabView). The voltage measurements are able to be calculated up to six decimal points of precision. Due to its low-cost implementation and the simplicity of the sensor, the prototype is suitable for basic measurements in applications such as altitude, blood pressure or water pressure.

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