Intelligent Control and System Engineering 2023; 1(1): 196.
Original Research Article

DSP implementation of calibration algorithm for piezoresistive pressure sensor

Feng Li, Jianhang Yu, Ying Gao, Yanfeng Jiang*

Department of Electrical Engineering, School of Internet of Things (IoTs), Jiangnan University, Wuxi 214122, Jiangsu Province, China

*** Corresponding author:** Yanfeng Jiang, jiangyf@jiangnan.edu.cn

ARTICLE INFO

Received: 8 August 2023
Accepted: 26 September 2023
Available online: 20 November 2023

doi: 10.59400/icse.v1i1.196

ABSTRACT: In this paper, a novel calibration algorithm for piezoresistive pressure sensors is proposed to address the problems of deviation from the zero point, nonlinearity, zero temperature drift, sensitivity temperature drift, etc. Firstly, the data is obtained through experimental tests. On the basis of analyzing the calibration principle of the pressure sensor calibration algorithm, the calibration coefficients are calculated. Then, the calibration algorithm is applied to obtain the calibrated output. In order to make the calibration algorithm applied to a high-end pressure sensor with a reduced cost, the calibration algorithm is implemented into a DSP chip (Digital Signal Processing). With the consideration of floating-point arithmetic processing and error interception, the synthesized DSP chip shows the advantages of fast arithmetic speed and low cost, which is of good value for engineering applications.

KEYWORDS: piezoresistive pressure sensor; calibration; temperature compensation; FPGA verification

1. Introduction

The pressure sensor is one of the key sensors in an industrial control system. Its accuracy and stability directly affect the function, performance, and reliability of the control system[1]. In practice, the widely applied piezoresistive pressure sensor includes four resistors in the Wheatstone bridge. Due to unavoidable process factors, the four resistors cannot have exactly the same resistance values, resulting in a degradation in the accuracy and reliability of the sensor[2]. The sensor output is varied with the temperature, leading to temperature drift, zero drift, sensitivity drift, and nonlinearity. With the development of science and technology, micro-mechanical (MEMS) systems are widely used in pressure sensors, which can improve the accuracy and reliability of the pressure sensor.

Currently, the commonly used compensation algorithms for the temperature drift of the pressure sensor include hardware compensation and software compensation[3]. Also, a dual Wheatstone bridge method is proposed to compensate for the pressure sensor temperature drift[4]. By using on-chip heaters and temperature-sensing electrodes, a thermostatic control loop is realized, thus eliminating the dependence of the pressure sensor output on the ambient temperature[5]. Compared with the software compensation, the hardware circuit-based compensation is easier to operate. However, in the actual test, there are many factors affecting the circuit. It is difficult to adjust the hardware circuit in real time to compensate for the influence of the temperature.

Software compensation utilizes a calibration algorithm in conjunction with a microprocessor to compensate for the output of the piezoresistive pressure sensor. It is mainly used to compensate for the zero drift, sensitivity drift, and nonlinearity of the pressure sensor. The pressure sensor calibrated by the software compensation always shows good linear output within the entire temperature range. Software compensation shows more flexibility and higher accuracy compared with hardware compensation. With the development of computer technology, software compensation using digital signal processing (DSP) technology has gradually become a research hotspot.

Software compensation methods include the look-up table method[6], the interpolation method[7,8], the BP neural network method[9,10], the wavelet neural network method[11], and the curve and surface fitting method[12,13]. The look-up table method is the simplest method of output compensation, which is based on the principle that the actual output values of the corresponding pressures at different temperatures are measured in the ambient chamber and correspond to the ideal linear output curve to form two-dimensional coordinate data, which is stored in the memory. When the device is working, the corresponding compensated pressure value can be read out based on the sensor output and the measured real-time temperature. This method can improve the temperature drift and nonlinearity of the sensor to a large extent. The compensation accuracy is positively correlated with the number of test points. The technical threshold is low. However, the compensation efficiency is not high, with a large amount of memory space occupied. Interpolation is used to characterize the temperature and the pressure by using formulas such as Newton interpolation, spline interpolation, Lagrange interpolation[14], etc., which provide a finer representation of the sample data when the boundary data are known. However, when the number of interpolations is too large, it is prone to the Runge phenomenon, which leads to the oscillation of the compensation results at the boundary. Surface fitting, also known as polynomial fitting, usually utilizes a two-dimensional polynomial characterization of temperature and pressure and solves for the polynomial coefficients based on the least squares method to compensate for the temperature drift[15]. This method is simple to implement and has a high calibration accuracy, which makes it a widely used sensor calibration method. However, when higher accuracy is pursued, the required number of least squares fits is too high, which could lead to pathological problems and singular equations. The polynomial coefficients cannot be solved, which makes this calibration compensation model less reliable.

Meanwhile, in an Industry 4.0 environment, the data generated by sensor networks requires artificial intelligence (AI) and computational intelligence (CI) to apply close-to-real-time data analysis techniques[16]. Thus, the research on the AI method is being more and more broadly investigated. At present, the AI method mainly adopts the BP neural network method, the wavelet neural network method, and other methods, which can effectively improve the measurement accuracy of the sensor[17,18]. The BP neural network optimizes the update of weights and thresholds by both forward transmission and error-reverse transmission, which can calibrate the sensor output characteristics well after repeated learning and training. However, the method has the disadvantages of slow convergence, being easy to fall into local extremes, and uncertainty of weight thresholds, which makes the generalization ability of the BP neural network highly contingent. Moreover, neural network methods have the disadvantage of network instability, i.e., long training times, which is not favorable for engineering applications[19].

Overall, AI algorithms use microcomputers and deep learning algorithms to optimize the output model in real-time and can provide higher output accuracy. The deep learning algorithms require a large number of calibration points to be extracted and computed. So, the calibration response time is longer. The introduction of microcomputers has greatly increased the cost of calibration. Currently, AI calibration methods tend to exist in the laboratory stage. On the contrary, numerical analysis methods tend to be simple to operate, low-cost, fast response time. It can be anticipated that compensation accuracy can reach or even exceed that of AI algorithms by choosing the right numerical analysis method. Therefore, industrial applications prefer numerical analysis methods.

In the paper, a new software calibration algorithm is proposed for the piezoresistive pressure sensor problem. The algorithm has low computation. No microcomputer is needed in the calibration, which can reduce the calibration cost and save power consumption. At the same time, the nonlinearity and temperature drift of the sensor output results can be greatly improved.

The proposed algorithm can be used to compensate for the zero drift and the sensitivity drift of the output of the piezoresistive pressure sensor with second-order temperature compensation. Furthermore, the nonlinearity of the output can be calibrated by the third-order compensation.

In the paper, the principle of the proposed calibration algorithm is analyzed. Then, the calibration coefficients of the calibration algorithm are calculated using the raw data measured by the pressure sensor. Since the hardware system is not capable of floating point operations, a fixed point design for floating point operations is required to determine the individual multiplication coefficients and the output bit widths. In this way, the fixed-point model is set up, which can achieve the desired performance with the calibrated output. RTL (Register Transfer Level) implementation is performed in Verilog and verified based on the FPGA platform. The results of this novel calibration algorithm based on DSP implementation show improved output performance for the pressure sensor.

2. Pressure sensor temperature calibration algorithm

2.1. Calibration algorithm analysis

The proposed calibration algorithm can be expressed with the following equations:

$$offset = off + t_{c1} \times (T - T_{stand}) + t_{c2} \times (T - T_{stand})^2 \tag{1}$$

$$sensitivity = s_0 + t_{s1} \times (T - T_{stand}) + t_{s2} \times (T - T_{stand})^2 \tag{2}$$

$$V'_{out} = (V_{in} - offset) \times sensitivity \tag{3}$$

$$\mathrm{V_{out}} = \mathrm{k} \times (\mathrm{V'_{out}} - \mathrm{V_0}) + \mathrm{k_s} \times (\mathrm{V'_{out}} - \mathrm{V_0})^2 + \mathrm{k_{ss}} \times (\mathrm{V'_{out}} - \mathrm{V_0})^3 \tag{4}$$

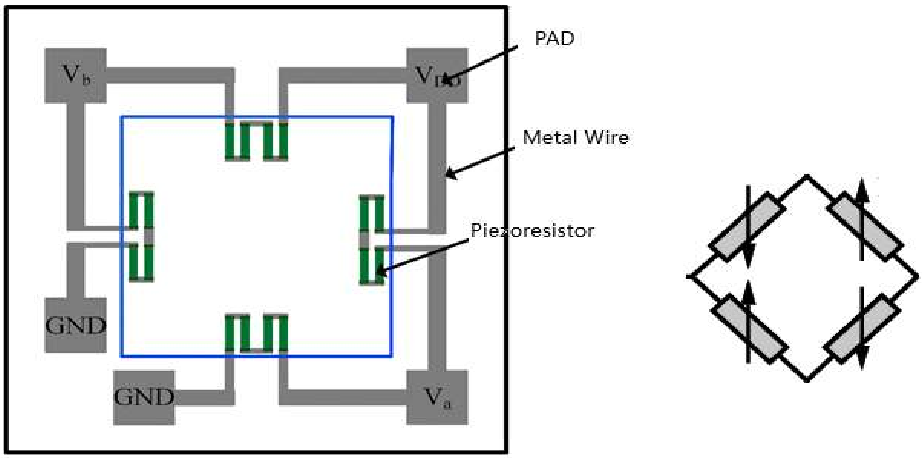
The offset denotes the zero drift. T_{stand} denotes the polynomial fit temperature reference point, which can be preset to the middle of the total temperature range. The sensitivity denotes the result of $\Delta V_{out}/\Delta V_{in}$, and it is worth noting that the sensitivity here is not the sensitivity of the sensor's output characteristics $\Delta P/\Delta V$ or $\Delta V/\Delta P$. Both offset and sensitivity are temperature-dependent.

V_{in} denotes the output voltage of an uncalibrated pressure sensor. V_0 indicates that the pressure sensor’s calibrated output is zeroed out. V_{out} shows the final output voltage value of the pressure sensor after calibration. The calibration coefficients, including off, t_{c1}, t_{c2}, s_0, t_{s1}, t_{s2}, k, k_s and k_{ss}, are the important parameters for the calibration algorithm.

The higher the order of the polynomial expansion in the calibration algorithm, the higher the calibration accuracy would be. However, the pressure sensor with higher accuracy is required to be tested under more temperature and pressure conditions. Considering the accuracy requirements of the pressure sensor, the second-order temperature compensation is conducted for the zero drift and the sensitivity drift of the pressure sensor output, while the third-order compensation is used for the nonlinearity of the output. In order to calculate the nine calibration coefficients of the calibration algorithm, it is necessary to retrieve the raw data measured at three temperature points and four pressure points. Detailed information is shown in the following.

2.2. Principle of the calibration

The studied piezoresistive pressure sensor is shown in **Figure 1**. As shown in **Figure 1(a)**, there are four piezoresistors in the sensor, connected by metal wires and pads. Its equivalent circuit is shown in **Figure 1(b)**.



(a) **(b)**

Figure 1. (a) Schematic of piezoresistive pressure sensor; **(b)** Equivalent Circuit of the pressure sensor.

The ideal output characteristic curve of the piezoresistive pressure sensor after the calibration is shown in **Figure 2(a)**. It can be seen that the ideal output characteristic curve of the calibrated pressure sensor is zeroed, linearized and temperature independent, i.e., the relationship between the calibrated output voltage V_{out} and the input pressure P should be linear. However, the actual output curve of the piezoresistive pressure sensor is shown in **Figure 2(b)**. It shows that the output characteristic curve of the pressure sensor is susceptible to temperature, which leads to a non-unique relationship between the output voltage V_{in} and the input pressure P before the calibration. The main goal of the calibration is to get the output as shown in **Figure 2(a)** instead of **Figure 2(b)** for the pressure sensor.

According to the calibration algorithm, it is necessary to establish the functional relationship between V_{out} and V_{in}. Using the ideal output characteristic curve of the pressure sensor in **Figure 2(a)**, the pressure P = V_{out}/slope can be obtained, i.e., the horizontal coordinate pressure P in **Figure 2(b)** is changed to be V_{out}/slope so that the functional relationship between V_{out} and V_{in} is established. However, **Figure 2(b)** is a function of V_{in} vs. V_{out}, and what we need to establish is a function of V_{out} vs. V_{in} in **Figure 2(c)**.

According to the calibration algorithm, it is necessary to establish the functional relationship between V_{out} and V_{in}. Using the ideal output characteristic curve of the pressure sensor in **Figure 2(a)**, the pressure P = V_{out}/slope can be obtained, i.e., the horizontal coordinate pressure P in **Figure 2(b)** is changed to be V_{out}/slope so that the functional relationship between V_{out} and V_{in} is established. However, **Figure 2(b)** is a function of V_{in} vs. V_{out}, and what we need to establish is a function of V_{out} vs. V_{in} in **Figure 2(c)**.

In **Figure 2(b)**, the zero drift offset 1–offset 3 at three temperatures are labeled, indicating the

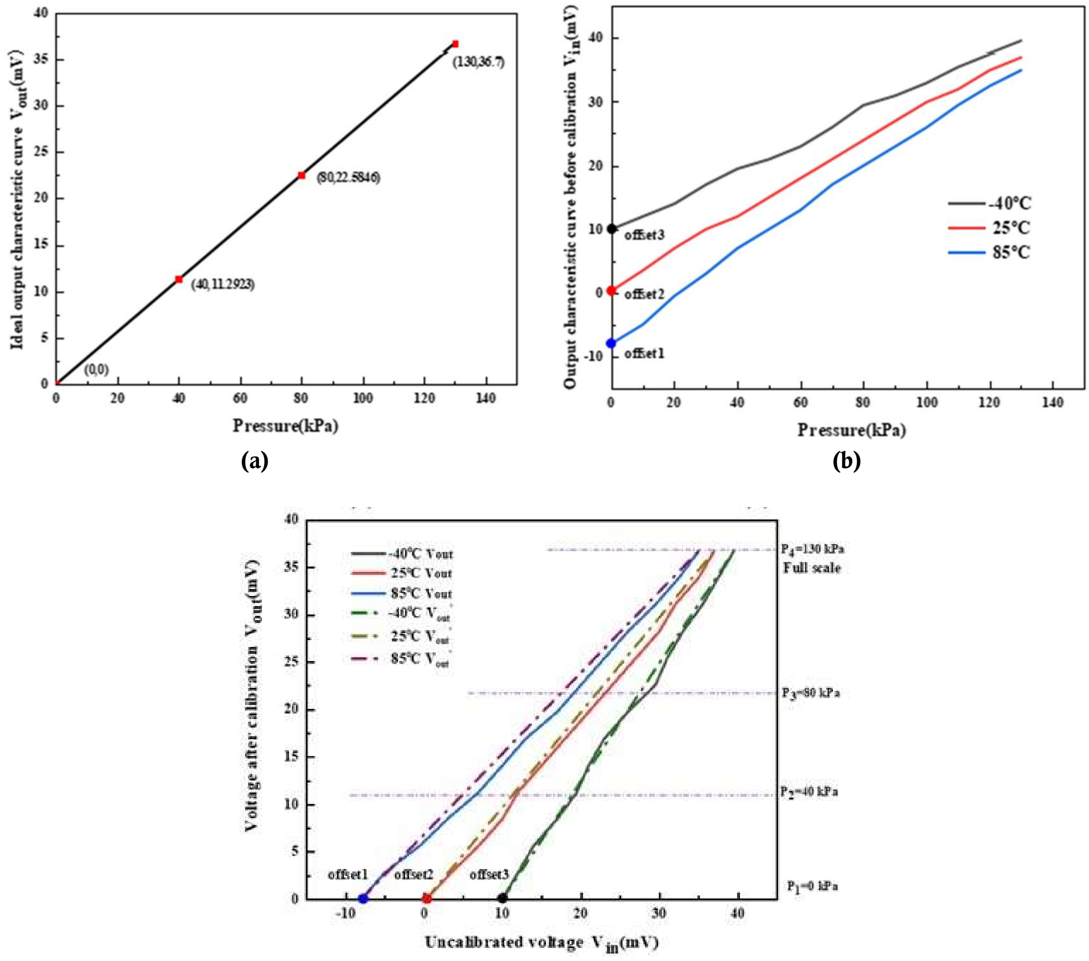


Figure 2. **(a)** Ideal output characteristic curve of the pressure sensor (target curve after calibration); **(b)** Output characteristic curve of a pressure sensor before calibration; **(c)** Output characteristic curve of the pressure sensor after calibration.

existence of the output voltage when the input pressure is 0 kPa. This would deteriorate the performance of the pressure sensor. The zero drift offset versus temperature T is given by Equation (1). In order to establish a functional relationship between V_{out} and V_{in}, as shown in **Figure 2(c)**, the slopes of the three dashed line segments indicate sensitivity sensitivity1 ~ sensitivity3. Sensitivity is the ratio of the difference between the ideal output voltage and the original output voltage when P is full scale and P is 0 kPa. The sensitivity can be expressed as:

$$sensitivity = \frac{V_{out130} - V_{out0}}{V_{in130} - V_{in0}} \tag{5}$$

So far, the functional relationship between the three dashed lines at the three temperatures in **Figure 2(c)** can be expressed with Equation (3). However, the calibration is aimed at the three real curves in **Figure 2(c)**, which cannot be expressed in terms of a deterministic functional relationship and need to be expressed indirectly by other functions. Although the three real curves are nonlinear, a rough linear line can be obtained first, as shown in **Figure 2(c)**, which has clear function representations as shown in Equation (3).

Equation (4) is the functional equation of the real curve obtained indirectly based on Equation (3). In Equation (4), V_0 is the point at which the output characteristics are guaranteed to cross zero after calibration at any temperature. When $T = T_{stand}$, $P = 0$, and $V_{out} = 0$, it can be obtained that $V'_{out} = V_0$

and $V'_{out} = 0$, therefore, $V_0 = 0$. K, k_s, and k_{ss} denote the degree of curvature of the imaginary straight line, by fitting the three imaginary straight lines, the degree of curvature of the imaginary straight line can be determined. The functional equation of the real curve can be indirectly obtained. It can be found that the calibrated voltage V_{out} versus pressure P is not affected by temperature, which proves that the calibration algorithm is correct.

3. Implementation of pressure sensor calibration algorithm

3.1. Data acquisition

The piezoresistive pressure sensor (as shown in **Figure 1(a)**) that needs to be calibrated is affixed with an auxiliary temperature sensor and placed into a temperature-adjustable airtight temperature chamber. The test diagram is shown in **Figure 3**. The external pressurized equipment, DC power supply, and data acquisition equipment are connected to the pressure sensor.

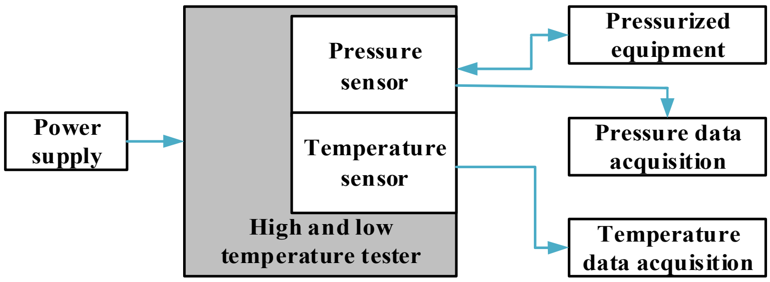


Figure 3. Schematic diagram of pressure sensor data acquisition.

Table 1 shows the experimental data of the pressure sensor.

Table 1. Experimental data of the pressure sensor.

Temperature (°C) / Pressure (kPa)	−40	−20	0	25	40	55	85
	Output voltage (mV) (Experimental measured under different pressures and temperatures)						
0	10	6.5	3	0.3	−2	−3.85	−8
10	12	9	6	3.5	1.5	−0.75	−5
20	14	12	10	7	5	3.25	−0.5
30	17	14.5	12	10	7	6.5	3
40	19.5	17.25	15	12	10.5	9.5	7
50	21	19.5	18	15	14	12.5	10
60	23	21.75	20.5	18	17	15.5	13
65	24.5	23.125	21.75	19.5	18.5	17.25	15
70	26	24.5	23	21	20	19	17
80	29.5	28.25	27	24	23.5	22	20
90	31	29.5	28	27	25	25	23
100	33	31.75	30.5	30	28.5	28	26
110	35.5	34.25	33	32	30.5	30.75	29.5
120	37.5	36.75	36	35	34.5	33.75	32.5
130	39.5	38.75	38	37	36.5	36	35

3.2. Calculation of calibration parameters

The experimental data collected from the pressure sensor is used to calculate the calibration coefficients for the calibration algorithm. According to the calibration algorithm described previously, three temperatures and four pressures are chosen to extract the corresponding data. It should be noted that when the pressures and the temperatures are selected, the endpoint values and the intermediate values should be selected for the calculation of the calibration parameters. In this way, a better fitting effect can be achieved with higher calibration accuracy.

The nine calibration coefficients solved based on the above calculations are shown in **Table 2**.

Table 2. Solved calibration coefficients.

Coefficients	Off	t_{c1}	t_{c2}	s_0	t_{s1}	t_{s2}	k	k_s	k_{ss}
Value	0.3	−0.1436	8.7179e−05	1	−0.0031	1.0504e−05	1.0285	−0.0076	1.8553e−04

The calibration algorithm combined with the calibration coefficients can be used to calibrate the pressure sensor. In order to verify the feasibility of the calibration algorithm, the novel software calibration algorithm is first calibrated to the experimental data of the pressure sensors by MATLAB. Furthermore, the DSP chip is synthesized by the RTL implementation and verified by the FPGA platform.

For the proposed algorithm combined with the calibration coefficients, float-point operations are needed. However, the floating-point operations are not supported in the hardware design. So, to solve the problem and to construct the DSP chip of the calibration algorithm, it is required to adjust the float-point operations into the fixed-point operations, while maintaining the accuracy. In order to ensure that the output has a certain degree of accuracy, 16 bits are selected for the decimal places of the fixed-point operation value, and 11 bits are selected for the integer places of the operation value. The final bit width of the nine calibration coefficients is set to be 28 bits, including the sign bit (the highest bit), 11 integer bits, and 16 decimal bits. In the test facilities, 10-bit ADC is used to convert the output of the pressure sensor into a digital value. V_{in} and T are set to be 10-bit signed numbers. The combinational logic circuit synthesized based on the calibration algorithm is used to perform the calculation. The output data is calculated using temporal logic.

3.3. Hardware implementation

In practical engineering applications, the sensor output circuit can use DSP as the core operation circuit to realize real-time digital temperature compensation. The specific circuit is shown in **Figure 4**. The ASIC chip, mainly includes the A/D conversion circuit, the synthesized DSP operation circuit, and EEPROM.

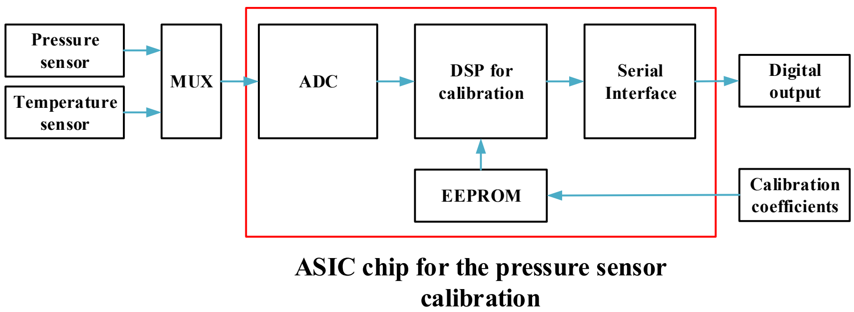


Figure 4. Hardware diagram for the calibration of the pressure sensor.

As shown in **Figure 4**, the EEPROM is implemented in the ASIC chip. The calculated calibration coefficients are stored in the memory beforehand. The pressure sensor output voltage value V_P and the temperature sensor output voltage value V_T are converted into digital values by the ADC in ASIC. The converted data are sent to the DSP operation circuit. Combined with the calibration coefficients stored in EEPROM, the DSP runs the calibration algorithm to calculate the calibrated output. Finally, the calibrated result is processed through the parallel-to-serial conversion circuit to realize the real-time digital temperature compensation of the pressure sensor.

4. Digital simulation and verification

Firstly, after completing the RTL design, the synthesized circuit is verified by both MATLAB and FPGA platforms. The floating-point coefficients, the voltages, and the temperatures are calculated by MATLAB. Then, the floating-point values are converted into the fixed-point data. **Figure 5** shows the detailed design of the FPGA-based implementation of the calibration algorithm.

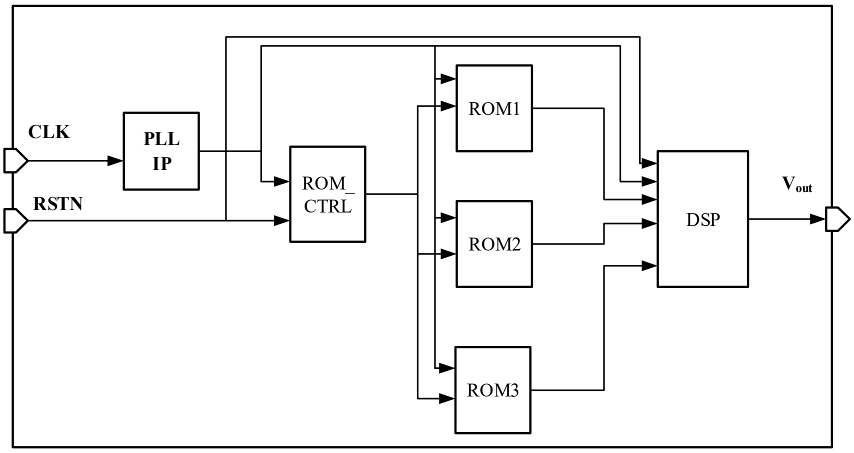


Figure 5. Detailed design diagram of FPGA implementation of the calibration algorithm.

As shown in **Figure 5**, ROM1, ROM2, and ROM3 are used to store the converted fixed-point data. ROM_CTRL is used to specify the addresses of ROM. The purpose of the divider PLL IP core is to reduce the clock signal of the FPGA to prevent possible timing errors. The DSP is the synthesized circuit based on the calibration algorithm. Xilinx's Vivado is adopted in the FPGA verification. The software mainly completes the implementation of the algorithm, and the RTL code synthesis, layout, and wiring are conducted based on the FPGA platform. The synthesized circuit and the coefficients are loaded into the FPGA development board. The calibrated results are uploaded to PC (Personal Computer) for analysis through the Integrated Logic Analyzer ILA (Integrated Logic Analyzer).

For the validation of the pressure calibration algorithm, based on the existing experimental data, it can be found that the output voltage value of the pressure sensor is the dependent variable, while the pressure value and the ambient temperature are the independent variables. The experimental data are listed in **Table 1**. The output hexadecimal data after calibration in the FPGA is imported into MATLAB and converted to floating point decimal data for data analysis. The main parameters for measuring pressure sensors are:

$$\delta = \frac{\Delta V_{max}}{V_{max}} \times 100\% \tag{6}$$

where δ is the relative error, ΔV_{max} is the maximum overwhelming error of the measurement, and V_{max}

is the full-scale output.

The relative errors of the voltage values before and after calibration are shown in **Figure 6**. The relative error in the range from 0 kPa to 130 kPa without calibration can be as high as 49.5%, while the relative errors after MATLAB and RTL calibration can be obviously minimized into 4.5% and 7.66%, respectively. Based on the calculations, the accuracy of the pressure sensor before calibration, the accuracy after MATLAB calibration, and the accuracy after RTL calibration are shown in **Table 3** below. The data in **Figure 6** and **Table 3** show that the calibration algorithm was able to significantly improve the output accuracy of the pressure sensor.

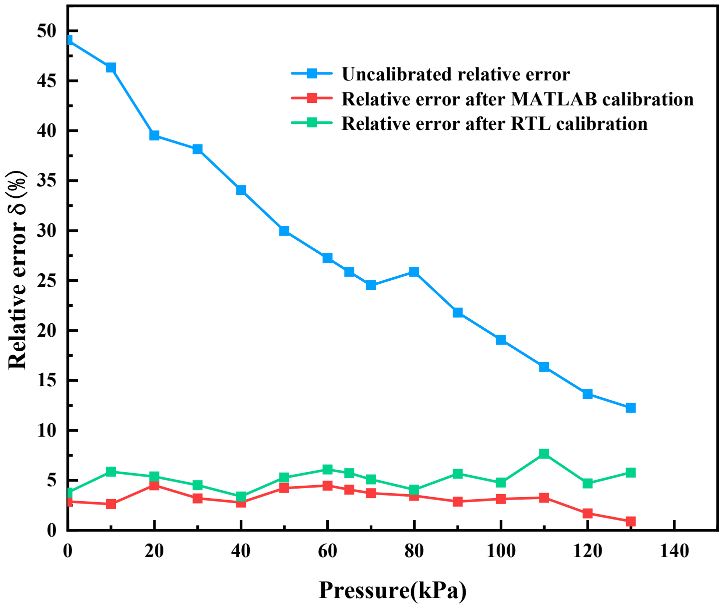


Figure 6. Errors of the pressure sensor before and after the calibration.

The comparison between the MATLAB calibration and RTL calibration is also shown in **Table 3**.

Table 3. Comparison of calibration accuracy.

	Uncalibrated	MATLAB calibration	RTL calibration
Calibration accuracy	27.25% FS	4.10% FS	4.63% FS

The comparison between the MATLAB calibration and the RTL calibration is shown in **Figure 6**. It can be seen that the error by the RTL calibration is slightly higher than that of the MATLAB calibration. The following two aspects are the main reasons for the degradation. Firstly, the calibration coefficients in RTL calibration are the fixed-point data, which are truncation errors by the data interception from the float-point data. Secondly, 10-bit ADC is used in the hardware. The pressure sensor output V_P and the temperature sensor output V_T are converted by the 10-bit signed A/D converter. So the systemic limitation can cause the error. Increasing the number of bits in the ADC and the bit width of the calibration coefficients could be effective in improving the calibration accuracy. However, a compromise should be considered regarding the accuracy, the area of the synthesized circuit, and the power consumption.

Figure 7 shows the actual results based on the fabricated piezoresistive pressure sensor with and without calibration. The data before calibration is shown in **Figure 7(a)**. **Figure 7(b)** shows the calibrated results of the calibration algorithm in MATLAB, and **Figure 7(c)** shows the calibrated results of the DSP. Based on the actual results, the proposed novel calibration algorithm can be used to optimize the zero temperature drift, the sensitivity temperature drift, the nonlinearity, and the zero non-zeroing problems of the piezoresistive pressure sensor. The relative error of the RTL calibration is a little bit larger than that of the MATLAB calibration.

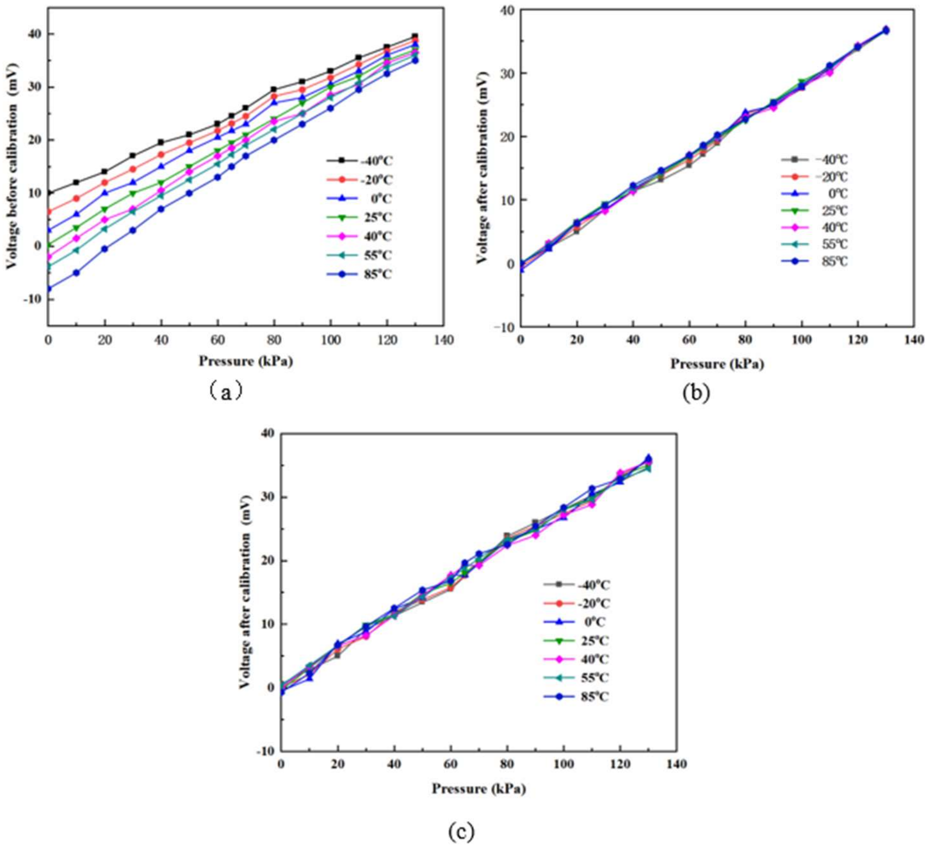


Figure 7. (a) Output characteristics before calibration; **(b)** Output characteristics after MATLAB calibration using the calibration algorithm; **(c)** Output characteristics after calibration using RTL implementation of the calibration algorithm.

The RTL calibration approach is suitable for industrial applications with the benefits of stand-alone and low-cost, etc. The problems of the linearity and the non-zeroing of the zero point can be solved effectively by the RTL approach. The operations in the processing of the floating-point data and the interception can lead to higher errors compared with the MATLAB approach. However, the RTL calibration could have wide application potentials in the engineering smart systems.

5. Conclusions

In the paper, the principle of the novel calibration algorithm is proposed, which can be used to solve multiple problems in the piezoresistive pressure sensor, including temperature drift, zero drift, sensitivity drift, nonlinearity, etc. The RTL-level circuit design of the temperature compensation algorithm is carried out in conjunction with the practical engineering application of real-time temperature compensation. The experimental results show that the circuit is effective in compensating the temperature of silicon piezoresistive pressure sensors, which can improve the linearity performance of the sensors and meet the characteristic requirements. An ASIC circuit is designed based on the synthesized calibration approach, including the EEPROM memory for the coefficient storage and the DSP circuit. Compared with the calibrated results by MATLAB, the RTL calibration method shows good engineering application potential. The ASIC chip based on the proposed algorithm and the designed circuit can be implemented stand-alone. It can be integrated with the pressure sensor with a low cost and small area. Compensated pressure sensors can be applied to pressure measurement of pipelines in petroleum and chemical industries. The novel calibration algorithm proposed in this paper can effectively improve the accuracy of the sensor. In future work, the error of the calibrated accuracy should be improved by using appropriate software algorithms or by increasing the number of bits of the ADC. The bit width of the calibration coefficients under the premise of low power consumption should be increased for better performance.

Author contributions

Conceptualization, YJ and FL; methodology, FL and JY; software, FL; validation, FL, JY, and YG; formal analysis, YJ and FL; investigation, YJ; resources, YJ; data curation, FL; writing—original draft preparation, FL, JY and YJ; writing—review and editing, YJ; visualization, YJ; supervision, YJ; project administration, YJ; funding acquisition, YJ. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors claim no conflict of interest in the paper.

References

1. Wang H, Zhang C, Zhao JP. Design and certification of conditioning circuit for silicon piezo-resistive pressure sensors. *Instrument Technique and Sensor* 2022; 11: 7–11. doi: 10.3969/j.issn.1002-1841.2022.11.002
2. Leng Y, Zhao G, Li Q, et al. A high accuracy signal conditioning method and sensor calibration system for wireless sensor in automotive tire pressure monitoring system. In: Proceeding of the 2007 International Conference on Wireless Communications, Networking and Mobile Computing; 21–25 September 2007; Shanghai, China. doi: 10.1109/WICOM.2007.459
3. Su Y, Sun YC, Li G. Comparing the different arithmetic methods for the offset drift compensation of pressure sensor. *Chinese Journal of Sensors and Actuators* 2004; 17(3): 375–378. doi: 10.3969/j.issn.1004-1699.2004.03.006
4. Luo XL, Xu TB, Bi LH. Research on compensation method of temperature drift in pressure sensor using double wheatstone-bridge method. *Advanced Materials Research* 2012; 459: 311–314. doi: 10.4028/www.scientific.net/AMR.459.311
5. Bruyker DD, Puers R. Thermostatic control for temperature compensation of a silicon pressure sensor. *Sensors and Actuators A: Physical* 2000; 82(1–3): 120–127. doi: 10.1016/S0924-4247(99)00321-0
6. Samy I, Postlethwaite I, Gu DW. Unmanned air vehicle air data estimation using a matrix of pressure sensors: A comparison of neural networks and look-up tables. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 2011; 225(7): 807–820. doi: 10.1177/0954410011399040
7. Li Y, Du B, Wei H, Li X. Research on intelligent pressure sensor compensation method. *Automation & Instrumentation* 2022; 2: 18–21. doi: 10.14016/[j.cnki.1001-9227.2022.02.018
8. Wang J, Hu G, Li J, et al. Research on temperature compensation of piezo-resistive pressure sensor based on Newton interpolation and spline interpolation. In: Proceedings of the 2021 IEEE 15th International Conference on Electronic Measurement & Instruments (ICEMI); 29–31 October 2021; Nanjing, China. pp. 109–113. doi: 10.1109/ICEMI52946.2021.9679505
9. Li GY, Sun YC, Pan GE, et al. Information fusion of pressure sensor based on bp network. *Chinese Journal of Scientific Instrument* 2005; 26: 168–171. doi: 10.3321/j.issn:0254-3087.2005.02.014.
10. Chen P, Chen N. A new method compensate temperature of pressure sensor. *Computing Technology And Automation* 2009; 28(4): 49–52. doi: 10.3969/j.issn.1003-6199.2009.04.013
11. Zhao H, Wang X. The method based on wavelet neural networks to compensate pressure sensor's temperature error. *Instrumentation Technology* 2007; 12: 45–47. doi: 10.3969/j.issn.1006-2394.2007.12.018
12. Yu J, Li J, Dai Q, et al. Temperature compensation and data fusion based on a multifunctional gas detector. *IEEE Transactions on Instrumentation and Measurement* 2015; 64(1): 204–211. doi: 10.1109/TIM.2014.2332242
13. Badura M, Batog P, Drzeniecka-Osiadacz A, Modzel P. Regression methods in the calibration of low-cost sensors for ambient particulate matter measurements. *SN Applied Sciences* 2019; 1: 622. doi: 10.1007/s42452-019-0630-1

14. Gaynullin B, Hummelgård C, Mattsson C, et al. Advanced pressure compensation in high accuracy NDIR sensors for environmental studies. *Sensors* 2023; 23(5): 2872. doi: 10.3390/s23052872
15. Wolters R, Kateman G. The construction of simultaneous optimal experimental designs for several polynomials in the calibration of analytical methods. *Journal of Chemometrics* 1990; 4(2): 171–185. doi: 10.1002/cem.1180040208
16. Rojek I, Macko M, Mikołajewski D, et al. Modern methods in the field of machine modelling and simulation as a research and practical issue related to Industry 4.0. *Bulletin of the Polish Academy of Sciences Technical Sciences* 2021; 69(2): e136717. doi: 10.24425/bpasts.2021.136717
17. Zhou G, Zhao Y, Guo F, et al. A smart high accuracy silicon piezoresistive pressure sensor temperature compensation system. *Sensors* 2014; 14(7): 12174–12190. doi: 10.3390/s140712174
18. Xu S, Lu W, Zuo F. Research on temperature compensation for optical fiber pressure sensor based on PSO-BP neural network. *Instrument Technique and Sensor* 2016; 10: 1–5, 9. doi: 10.3969/j.issn.1002-1841.2016.10.001
19. Xu D, Liu Y. A temperature compensation algorithm of piezoresistive pressure sensor and software implementation. In: Proceedings of the 2013 IEEE International Conference on Mechatronics and Automation; 4–7 August 2013; Takamatsu, Japan. pp. 1738–1742. doi: 10.1109/ICMA.2013.6618178.