Design of Read Circuitry for Nonlinear Smart Sensors

S Ananthi, Himanshu Chaudhary and Kulwant Singh
Electronics and Communication Engineering, Manipal University Jaipur, India
E-mail: ananthi232@gmail.com

Abstract. The purpose of this paper is comparative study, design and simulation of two stage, analog to digital convertor to convert the properly conditioned stepwise linearized analog output signal from a ratio metric NTC thermistor circuit. The design part consists of linearization of thermistor temperature- resistance characteristics in analog domain. A CMOS sample and hold circuit is used to bridge linearizing circuit in analog domain and the flash ADC circuit in digital domain. Ratio of the voltage is sensed rather than absolute voltage across the thermistor, as part of linearization. Further linearization is done in two stage flash ADC consisting of a reference voltage divider resistance, comparators, analog multiplexers and 8bit differential ADC. A graph is plotted between temperature and the corresponding resistance of NTC thermistor NTCL-E100E10 [1], having a resistance of 10kΩ at 25ºC. The graph is an exponential curve and it is linearized [2] around 50ºC by drawing a curve between temperature and voltage ratio across a resistor connected in series to the thermistor. This curve is still nonlinear at extreme values of the considered range -20 ºC to 100 ºC. The full range is divided into four sub ranges and piecewise linearization is done simultaneously with analog to digital conversion. Analog and digital integrated circuits are generally low powered and the voltage limit is 5V. Thermistor is compatible in this range. A number of signal conditioning circuits are devised in the past. Here the linearizing steps involved in simple circuit elements and simple design. Signal conditioning of thermistor response has a number of design circuits already devised, still there is room for research to make it is small in size, low powered, high sensitivity and cost effective.

Index-Terms: Mathematical modelling, Nonlinear transfer function, piecewise linear analog signal, flash ADC

1. Introduction
Any sensor that senses a physical parameter produces an output electrical parameter. To convert this response of the sensor to a measurable level it must be amplified. To measure temperature four different types of sensors are commonly used [3]: infrared, thermocouple, RTD and thermistor. Kufre Esenowo et al [4] designed a thermal detector that can convert incident power into an electrical output and signal conditioning circuit &data acquisition elements for processing the chopped IR sensor signal. Rotating shutter is configured to supply the chopped signal. A multi sensor embedded system is developed [5] along with reconfigurable automation and communicating with host. It attempts to develop a generic platform to support hardware interface, sensors, communication and actuators. Results of developed prototype system with RTD temperature sensor, over a wireless connectivity for various distances are presented.
A smart CMOS sensor with a combined read out for temperature and humidity measurement [6] with low power consumption, high sensitivity, no post processing and small in size is designed. The design has two modes of operation and the sensor signal is converted into a digital code representing a frequency ratio between to oscillators. Lm35 is a calibrated readily available semiconductor sensor. [7] Shantanu et al. designed a signal conditioning circuit using Lm35. The designed system is divided into two parts, a personal unit and the base unit. A detailed design of biomedical sensors with the necessary signal conditioning circuit is presented.

A temperature sensor CMOS based, for the range -5°C to 120°C is designed and analyzed in [8]. It proposes a design with temperature range selection circuit, so that the thermistor linearizing circuit automatically switches to a corresponding linearity calibration loop and the method is implemented in TSMC 0.5μm CMOS high voltage mixed signal based polydice. A total of four states are described circuit. It is designed to extend sensing range through a temperature range auto selecting circuit. Output results demonstrate a high linearity with linearity error less than 1.4% is achieved. It resolves the problem that the temperature range of a single thermistor temperature sensor is too small.

An ANN based linearization of an NTC thermistor connected to an inverting operational amplifier is presented [9]. The nonlinearity of signal conditioning circuit due to temperature voltage characteristic of the thermistor is reduced with the help of ANN technique. A low cost linearizing circuit is developed [10] using inverting operational amplifier. The gain of the arrangement can be adjusted over a wide range by simply varying the feedback resistance. For a narrow span the linearity is ±0.5%.

This paper discusses with mathematical modeling of nonlinear response and its application to thermistor sensors. Analog signal is then converted into digital signal in two stages and finally by successive approximation register, an differential flash ADC converter having resolution of 8bit. The read circuitry for linearization of the signal from a thermistor is designed and simulated using Multisim12.0.

2. Mathematical modeling of thermistor
Thermistor is a Semiconductor material. It measures temperature through a corresponding change in its resistance. It has the highest sensitivity among all other temperature sensing elements, for a small change in temperature a large change in its resistance. In NTC type thermistor the resistance decreases as the temperature increases. But its response, change in its resistance with respect to change in temperature is highly nonlinear response. This nonlinearity of the sensing element causes low accuracy during measurement. Linearity is a desired property, because the sensitivity remains constant throughout the range since calibration can be done with fewer points. The characteristics of thermistor, temperature versus resistance can be modeled mathematically. The NTC thermistor NTCEL100E3103 is taken as example.

Referring to table 1, the thermistor has 10KΩ resistance at temperature 25°C. The temperature-resistance characteristics drawn in Fig.1, can be [11] expressed as

\[ R_T = R_0 \exp \left( \frac{\beta}{T} - \frac{\beta}{T_0} \right) \]  

Where,
\[ R_T \] = thermistor resistance at temperature T (K)
\[ R_0 \] = thermistor resistance at temperature T0 (K)
\[ T_0 \] = the reference temperature taken as (25+273) K
\[ \beta \] = the material property, assumed to be constant for a given temperature range.

Taking natural logarithm on both sides and performing some mathematical rearrangement of the parameters, the equation (1) becomes,

\[ T^* \left( \frac{T_0}{(T_0-T)} \right)^* \ln \left( \frac{R_T}{R_0} \right) = \beta \]  

(2)
Table 1. Temperature and the corresponding resistance of NTC thermistor NTCLE100E3103

| Temperature (°C) | Resistance of Thermistor $R_t$(Ω) | $V_{out} = 5/(1+R_t/R_s)$ (Volts) |
|------------------|----------------------------------|----------------------------------|
| -20              | 96358                            | 0.19                             |
| -15              | 72500                            | 0.25                             |
| -10              | 55046                            | 0.33                             |
| -5               | 42157                            | 0.42                             |
| 0                | 32554                            | 0.53                             |
| 5                | 25339                            | 0.66                             |
| 10               | 19872                            | 0.81                             |
| 15               | 15698                            | 0.99                             |
| 20               | 12488                            | 1.18                             |
| 25               | 10000                            | 1.4                              |
| 30               | 8059                             | 1.62                             |
| 35               | 6535                             | 1.856                            |
| 40               | 5330                             | 2.1                              |
| 45               | 4372                             | 2.34                             |
| 50               | 3605                             | 2.58                             |
| 55               | 2989                             | 2.82                             |
| 60               | 2490                             | 3.04                             |
| 65               | 2084                             | 3.25                             |
| 70               | 1753                             | 3.44                             |
| 75               | 1481                             | 3.61                             |
| 80               | 1256                             | 3.77                             |
| 85               | 1070                             | 3.9                              |
| 90               | 915.4                            | 4.04                             |
| 95               | 786                              | 4.15                             |
| 100              | 677.3                            | 4.25                             |

Fig. 1. Exponential relation between the parameters
Considering its mid temperature range resistance, \( R \) (at \( T=50°C \)) = 3605\,\Omega, \( \beta \) can be calculated using equation (2) as

\[
\beta = \frac{(298\times323)}{(298-323)} \times \ln \left( \frac{3605}{10000} \right) = 3928.17\,\Omega.
\]

Thus the n-type thermistor resistance decreases exponentially as the temperature increases.

### 2.1. Thermistor Linearization

The exponential relation between thermistor resistance and the temperature can be linearized by connecting it in a DC circuit with a parallel or series resistor [12]. A simplest linearization circuit containing thermistor with a series resistor is configured This acts as a voltage divider of the DC source as shown in Fig. 2.

\[
V_{out} = V_{in} \frac{R_S}{R_T + R_S} \tag{3}
\]

\[
V_{out} = V_{in} \frac{1}{1 + \frac{R_T}{R_S}} \tag{4}
\]

where \( R_T \) = thermistor resistance at temperature \( T \) (Kelvin).

\( R_s \) = series resistor connected to thermistor for linearization. As the temperature increases further \( R_T \ll R_S \) have a value near \( \approx V_{in} \). If the temperature is very low \( R_T \gg R_S \), \( V_{out} \) is very low value \( \approx 0 \). Hence \( (R_T / R_S) \) is a function of temperature. This can be verified from the table 1 as voltage across \( R_s \).

![Fig. 2. Series voltage divider circuit](image)

Substituting equation (1) in (4) for \( R_T \) and take second derivative & equate it to zero, gives point of inflection.

\[
R_T = R_0 \times \left( \frac{\beta - 2T_1}{\beta + 2T_1} \right) \times \exp \left( \frac{\beta}{T_1} - \frac{\beta}{T_0} \right) \tag{5}
\]

where \( T_1 \) = temperature of inflection.

In this linearization process temperature range is selected from - 25°C to 100°C, \( T_1 = 40°C \), \( R_0 = 10\,\text{K} \), \( T_0 = 25°C \) and \( \beta = 3928.17\,\text{K} \) which gives \( R_T = 3856.9\,\Omega \). \( V_{in} \) is taken as 5V and using equation (3), a plot for temperature versus \( V_{out} \) is drawn. Compared with Fig. 1, the graph drawn in Fig. 3, linearity is very much improved around \( T = 40°C \). But for wider range temperature measurement the nonlinearity at extremes in Fig. 3 is to be linearised. In this paper a method is proposed such that the nonlinearity is further improved in digital domain while performing A to D conversion.
2.2. Thermistor analog circuit

Output of the circuit is which is partially linearised is further processed by digital conditioning circuit by connecting through a unity gain op-Amp and a Sample and hold circuit [13] which is acting as a buffer for impedance matching as shown in Fig. 4.

3. Piecewise linearized design for thermistor sensor

While performing piecewise linearization the quantization steps is not linear. Generally they are based on two step conversion process [14]. First coarse conversion followed by the fine conversion. Coarse nonlinear conversion is done by flash ADC of fewer bits and the second step by differential eight bits flash ADC. The second conversion can also be done by a DAC, converting the coarse digital value into analog value, thereby restricting the input voltage for second conversion. But it need more area and consumes more power as explained in [15].

To improve the linearity and minimizing the quantization error nonlinear piecewise ADC can be used. The step size (for temperature range -20 to 100°C) is divided into 4, but the corresponding voltage steps are not equal due to the nonlinear transfer function analog output versus temperature as shown in Fig. 3.

Reference voltage for first stage is taken as 5V. Four unequal resistors [16] are used to set the reference voltages for comparators. These voltages represent the range of each segment of the piecewise linear transfer function. In Fig. 5 the segments are represented by differently colored straight line
segments. The voltages correspond to the temperatures obtained by dividing the total temperature range into four parts: -20-10, 10-40, 40-70 and 70-100°C as shown in Table 2.

**Table 2. Piecewise temperature range and the corresponding voltage range**

| Temperature range                  | (Centigrade) | Voltage (Volts) |
|-----------------------------------|--------------|----------------|
| Linear range 1                    | -20 to 10    | 0.192 to 0.813 |
| Linear range 2                    | 10 to 40     | 0.813 to 2.1   |
| Linear range 3                    | 40 to 70     | 2.1 to 3.44    |
| Linear range 4                    | 70 to 100    | 3.44 to 4.25   |

Below Fig. 5 shows the variation of voltage with respect to temperature divided into four segments, the four different segments are represented by different coloured straight line segments. Four different segments basically define a linear rise in voltage with the increase in temperature.

![Nonlinear Flash ADC transfer function](image)

**Fig. 5. Nonlinear Flash ADC transfer function.**

**4. The proposed method**

Flash ADC converts analog into digital with highest speed. It has very simple circuits but the number of comparators required increase exponentially as the number of output binary bit increases. In this paper, two stage of analog to digital conversion is done and the number of comparators used is only two. The total range of the analog input voltage is divided into two parts in stage 1. Out of the four linear ranges as given in table 2, one particular range is chosen by stage 2, which is explained below.

In stage 1, the middle value of the total range is given as reference voltage to the negative input terminal of first comparator (CompA) and sensor output voltage after sampling and hold is given to positive input terminal of the comparator (CompA).
Referring to the table 2, the total range of the analog signal is from 0.192 to 4.25 Volts. Voltage divider network is designed [14] such that the middle value is 2.1 Volts and it is given as Vref1 to compA. In Fig. 6, the input pins of Amux1 connections are as follows:

Pin1 is connected to 5Volt, pin4 and pin8 to $V_{ref1}$ and pin 11 to ground. The compA compares $V_{in}$ with $V_{ref1}$. CompA output is connected to Amux1 to control pin 13 and 5 & negated output is connected to control pin 6 and 12. Its output terminal pin 2 and 9 are interconnected (at a time only one goes high). Voltmeter U1 shows its reading. Its output terminal pin 3 and 10 are interconnected (at a time only one goes high). Voltmeter U2 shows its reading. If $V_{in} > V_{ref1}$, CompA output goes high. Amux1 Pin1 is connected to pin2 (internally since the control pin 13 goes high), the voltmeter U1 displays pin2 value. Amux1 Pin4 is connected to pin3 (internally since the control pin 5 goes high), the voltmeter U2 displays pin3 value.

If $V_{in} < V_{ref1}$, CompA output goes low. Amux1 Pin8 is connected to pin9 (internally since the control pin 6 goes high as a result of compA output negation), the voltmeter U1 displays pin9 value. Amux1 Pin11 is connected to pin10 (internally since the control pin 12 goes high as a result of compA output negation), the voltmeter U2 displays pin10 value. Comparator compB is connected to the node between the series resistors R4 and R5 (ref voltage for compB) the other terminal of R4 is connected to the interconnected junction between terminals pin 2 and 9 of Amux1. Other terminal of R5 is connected to the interconnected junction between terminals pin 3 and 10 of Amux1.
Fig. 7. Circuit connection between stage 1 and multiplexer of stage 2

The comparator B in Fig. 7 compares $V_{in}$ with $V_{ref2}$. The input pins of Amux2 connections are as follows: Pin1 is connected to interconnected junction between terminals pin 2 and 9 of Amux1. Pin4 and pin8 to $V_{ref2}$ of compB and pin 11 connected to interconnected junction between terminals pin 3 and 10 of Amux1. Going by the same procedure as that of Amux1, The compB compares $V_{in}$ with $V_{ref2}$. compB output is connected to Amux2 to control pin 13 and 5 & negated output is connected to control pin 6 and 12. Its output terminal pin 2 and 9 are interconnected (at a time only one goes high). Voltmeter U3 shows its reading. Its output terminal pin 3 and 10 are interconnected (at a time only one goes high). Voltmeter U4 shows its reading.

If $V_{in} > V_{ref2}$, compB output goes high. Amux2 Pin1 is connected to pin2, when control pin 13 goes high the voltmeter U3 displays pin2 value. Amux2 Pin4 is connected to pin3, when control pin 5 goes high the voltmeter U4 displays pin3 value. If $V_{in} < V_{ref2}$, compB output goes low. Amux2 Pin8 is connected to pin9, when control pin6 goes high the voltmeter U3 displays pin9 value. Amux2 Pin11 is connected to pin10, when control pin12 goes high the voltmeter U4 displays pin3 value.
In Fig. 8, the output of Amux2, either pin2 or pin9 is connected to $V_{ref2}^+$ and either pin3 or 10 to $V_{ref2}^-$ pins of 8bit differential ADC converter. $V_{in}$ is connected to the $V_{in}$ pin of 8 bit differential ADC converter. The output of 8bit ADC is shown in 8bit bar LED1

5. Simulated Results
The proposed circuit is simulated using Modelsim12.0. A variable voltage source is used to represent the analog output voltage of thermistor analog circuit, $V_{out}$. Four such cases are discussed one from each piecewise voltage range (and thereby representing the corresponding temperature range). The digital value shown by the LED1 is converted into decimal and compared with $V_{in}$, the input variable voltage value. From these four different cases the input results are compared with the simulated results.

**Case1:** When input voltage $V_{in}$ = 4.05 Volt
The displayed binary value is (64+32+8+2) = 106
$U3 = \text{voltmeter reading connected to } V_{ref2}^+ \text{ pin of ADC } = 4.994 \text{ Volt.}$
$U4 = \text{voltmeter reading connected to } V_{ref2}^- \text{ pin of ADC } = 3.371 \text{ Volt.}$

$V_{in}$ as calculated from simulated result = (106/256)*(4.994 - 3.371) + 3.371 = 4.0459 Volt.
Here, it can be seen that applied input voltage and simulated results are approximately equal.
Fig. 9. Simulated result Case1, $V_{in} = 4.05$ Volt

**Case2:** When input voltage $V_{in} = 2.7$ Volt  
The displayed binary value is $(64+32+8+4+1) = 109$.  
$U_3 =$ voltmeter reading connected to $V_{ref+}$ pin of ADC =3.371Volt  
$U_4 =$ voltmeter reading connected to $V_{ref-}$ pin of ADC =2.194Volt.  
$V_{in}$ as calculated from simulated result = $\frac{(109/256) \times (3.371 - 2.194)}{1} + 2.194 = 2.695$ Volt.  
Here, it can be seen that applied input voltage and simulated results are approximately equal.

Fig. 10. Simulated result, Case2: $V_{in} = 2.7$ Volt

**Case3:** When input voltage $V_{in} = 1.575$ Volt  
The displayed binary value is $(128+16+8+4) = 156$
U3 = voltmeter reading connected to $V_{ref}^+$ pin of ADC = 2.026 Volt.
U4 = voltmeter reading connected to $V_{ref}^-$ pin of ADC = 0.864 Volt.

$V_{in}$ as calculated from simulated result = $(156/256) \times (2.026 - 0.864) + 0.864 = 1.572$ Volt.

Here, it can be seen that applied input voltage and simulated results are approximately equal.

**Fig. 11.** Simulated result, Case 3: $V_{in} = 1.575$ Volt

**Case 4:** When input voltage $V_{in} = 0.45$ Volt.
The displayed binary value is $(128+4+1) = 133$.
U3 = voltmeter reading connected to $V_{ref}^+$ pin of ADC = 2.026 Volt.
U4 = voltmeter reading connected to $V_{ref}^-$ pin of ADC = 0.864 Volt.

$V_{in}$ as calculated from simulated result = $(133/256) \times 0.864 = 0.4478$ Volt.

Here, it can be seen that applied input voltage and simulated results are approximately equal.

**Fig. 12.** Simulated result, Case 4: $V_{in} = 0.45$ Volt.
6. Error Calculation
For more input voltage values, the decimal equivalent of displayed binary values are calculated and the same is tabulated in table 3.

Table 3. Calculation of error between input voltage and measured value by the proposed circuit design

| $V_{in}$ from variable voltage source | Range shown by Multiplexer Amux1 | Range shown by Multiplexer Amux2 | Voltage calculated from binary display LED1 | Error % |
|--------------------------------------|----------------------------------|----------------------------------|---------------------------------------------|---------|
| 3.825                                | 4.994, 2.196                     | 4.994, 3.376                     | 3.8247                                      | 7.8*10^-3 |
| 3.6                                 | 4.994, 2.196                     | 4.994, 3.376                     | 3.59                                        | 0.277   |
| 2.92                                | 4.994, 2.196                     | 3.371, 2.194                     | 2.92                                        | 0       |
| 2.475                                | 4.994, 2.196                     | 3.371, 2.194                     | 2.4744                                      | 0.0242  |
| 2.025                                | 2.026, 0                         | 2.026, 0.862                    | 2.026                                       | 0.049   |
| 1.125                                | 2.026, 0                         | 2.026, 0.862                    | 1.122                                       | 0.266   |
| 0.675                                | 2.026, 0                         | 0.862, 0                        | 0.674                                       | 1.48    |
| 0.225                                | 2.026, 0                         | 0.862, 0                        | 0.222                                       | 1.33    |

7. Conclusion
Partial linearization of sensors characteristics in analog domain is done by passive circuit elements. Using two stage PWL flash ADC having inverse transfer function to that of sensor has improved performance. By using the proper ADC transfer function, linearization of nonlinear sensor characteristic is possible in digital domain. This will eliminate further correction circuits to handle the nonlinearity problem. A to D conversion and linearization are done simultaneously in digital circuitry, by which it is possible to make more efficient and cheap smart sensors. Nonlinearity is removed at acquisition speed.

The input range is divided into four linear ranges and the range in which sensor voltage falls is selected by using two comparators and two analog multiplexers. Out of four ranges, according to the input value only one range is linearly converted into digital domain by 8bit flash ADC converter. The simulated result by Multisim12.0 shows negligible error in higher three ranges and of the order of 1% in the fourth lower most range.

References

[1] R. Brown and R. Orange, “NTCLE100E3 Vishay BCcomponents NTC Thermistors , Radial Leaded , Standard Precision NTC10E3,” pp. 1–17.
[2] Thermistor Mathematics. (2011). Retrieved from http://mathscinotes.com/2011/07/thermistor mathematics/
[3] Trancă, D. C., Rosner, D., Tătăriou, R., Stegaru, S. C., Surpăţeanu, A., & Peišić, M. (2018, September). Precision and linearity of analog temperature sensors for industrial IoT devices. In 2018 17th RoEduNet Conference: Networking in Education and Research (RoEduNet) (pp. 1-6). IEEE.
[4] Jack, K. E., Etu, I., & Ukanide, V. N. (2016). The Design of a Signal Conditioning and Acquisition Elements of a Chopped Broadband Radiation Pyrometer. In Proceedings of the World Congress on Engineering and Computer Science (Vol. 1).
[5] Anand, C., Sadistap, S., Bindal, S., Botre, B. A., & Rao, K. S. N. (2010). Wireless multi-sensor
embedded system for Agro-industrial monitoring and control. International Journal on Advances in Networks and Services Volume 3, Number 1 & 2, 2010.

[6] Eder, C., Valente, V., Donaldson, N., & Demosthenous, A. (2014). A CMOS smart temperature and humidity sensor with combined readout. Sensors, 14(9), 17192-17211.

[7] Kodgirwar, S., Chandrachood, A., Vyas, S., & Kodgirwar, V. (2016). Design of Signal Conditioning Circuit for Biomedical Sensors and Battery Monitoring Circuit for a Portable Communication System. American Journal Of Engineering Research ( AJER ), (6), 100–107.

[8] Wang, C. C., Hou, Z. Y., & You, J. C. (2018). A high-precision CMOS temperature sensor with thermistor linear calibration in the (−5 C, 120 C) temperature range. Sensors, 18(7), 2165.

[9] Kumar, V. N., & Narayana, K. V. L. (2015). Development of thermistor signal conditioning circuit using artificial neural networks. IET Science, Measurement & Technology, 9(8), 955-961.

[10] Sarkar, A. R., Dey, D., & Munshi, S. (2013). Linearization of NTC thermistor characteristic using op-amp based inverting amplifier. IEEE Sensors Journal, 13(12), 4621-4626.

[11] Becker, J. A., Green, C. B., & Pearson, G. (1946). Properties and uses of thermistors—Thermally sensitive resistors. Electrical Engineering, 65(11), 711-725.

[12] Stankovic, S. B., & Kyriacou, P. A. (2011). Comparison of thermistor linearization techniques for accurate temperature measurement in phase change materials. In Journal of Physics: Conference Series (Vol. 307, No. 1, p. 012009). IOP Publishing.

[13] Rajput, A., Kanathe, S., & Bhopal, R. (2012). Design of sample and hold circuit. Int. J. Sci. and Research Publications, 2.

[14] Jovanović, J., & Denić, D. (2016). A Cost-effective Method for Resolution Increase of the Two stage Piecewise Linear ADC Used for Sensor Linearization. Measurement Science Review, 16(1), 28-34.

[15] Jovanović, J., Denić, D., & Jovanović, U. (2017). An Improved Linearization Circuit Used for Optical Rotary Encoders. Measurement Science Review, 17(5), 241-249.

[16] Lukić, J., & Denić, D. (2015). A Novel Design Of An NTC Thermistor Linearization Circuit. Metrology and Measurement Systems, 22(3), 351-362.