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Improving Accuracy of Temperature Measurement Using PRTD Sensing Element in Microcontroller Based System

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Abstract—*In advanced industrial and medical applications it is required to measure temperature over a wider range with higher accuracy, low cost and lower power consumption. Accuracy of ±1°C to ±0.1°C or even better is desired. If such an accuracy is required over a wide temperature range of -200°C to +800°C then platinum resistance temperature detector is the best choice of temperature sensing element. In this paper the techniques used in using PRTD for achieving high accuracy temperature measurement implemented in a microcontroller based measurement system is discussed and a corresponding scheme is proposed. The linearization technique used to overcome the non-linear characteristic of PRTD in the data acquisition software is also discussed.*

Keywords*: Microcontroller, Sensor, PRTD(Platinum Resistance Temperature Detector), Linearization, Pt100, Pt1000, ADC(Analog to Digital Converter), I2C(Inter Integrated Circuit)*

1. INTRODUCTION

Temperature sensing and precise control forms an integral part of any industrial monitoring and control system. Simpler applications, such as electronic thermometers monitoring outdoor temperatures or temperature monitors inside vehicles are used to measure ambient temperatures. More complex applications may use temperature data in a control loop, taking actions based on the data. For example, HVAC systems control heating and air-conditioning units to achieve desired indoor temperatures and computer memory modules employ thermal management techniques. These are just some of the many applications in which temperature sensor accuracy is vital for performance. Semiconductor sensors with an accuracy ±0.5°C(typical) and ±1°C(maximum) are feasible to be used with microcontrollers that doesn't require to be linearized, but the range of temperature over which the accuracy can be achieved is limited between -40°C to +120°C. Platinum resistance temperature detector offers the best accuracy and repeatablity over a temperature range of -200°C to +800°C and is ideal for industrial and medical applications. PRTD is non-linear in nature but linearisation options such as simple look-up table or more math intensive polynomial expression can be implemented easily in the microcontroller firmware in a microcontroller based temperature measurement system that uses PRTD as the temperature sensing element.

2. LITERATURE SURVEY

In september 30, 2011, an article[1] was published by Sohail Mirza of Maxim Integrated where the usage of PRTD for higher accuracy temperature measurement was discussed. In 29th August 2012, Stephen To of Silicon Labs published an article[2] where the different calibration techniques for a microcontroller based temperature measurement system was discussed. In January 2013 a paper by Dave Smith, "An introduction to MSP430 microcontroller based temperature sensing solution" was published where the options of using thermistors to semiconductor temperature sensing elements with microcontrollers were discussed.

3. BASIC SENSING ELEMENTS AND THEIR COMPARISON

The basic sensing elements that are used in industrial, medicine and commercial applications are thermocouple, resistance temperature detector(RTD), thermistor and semiconductor sensors(analog and digital). Table 1 gives a comparison of different parameters between these sensors for temperature measurement.

Table 1: Common temperature measurement devices

Criteria	***Thermocouple***	***RTD***	***Thermistor***	***Semiconductor***
Temperature range	Very wide (-200°C to +2000°C)	wide (-200°C to +800°C)	Narrow (-50°C to +300°C)	Narrow (-50°C to +200°C)
Accuracy	Medium	High	Medium	High
Repeatability	Fair	Excellent	Fair to good	Good to excellent

Long-Term stability	Poor to fair	Good	Poor	Good
Sensitivity	Low	Medium	Very high	High
Linearity	Fair	Good	Poor	Good
Response	Medium to fast	Medium	Medium to fast	Medium to fast
Lead Effect	High	Medium	Low	Low
Self heating	No	Very low to low	High	Very low to low

As it can be seen from Table 1, that for accurate measurement RTD as well as Semiconductor sensors can be used but in order to achieve the higher accuracy and repeatability over a wide range of temperature RTD is the best choice. Platinum is stable, and corrosion and oxidation do not affect it. Three common PRTDs are PT100, PT500 and PT1000 which exhibit resistance values of 100, 500 and 1000 ohm at 0°C. Typical PRTD is the PT1000 that has a resistance of 1KΩ at 0°C.

4. PRTD TEMPERATURE MEASUREMENT

Fig. 1 shows the 4-wire RTD temperature sensing scheme(Kelvin connection) for most accurate measurement at a distance and with dissimilar wires.

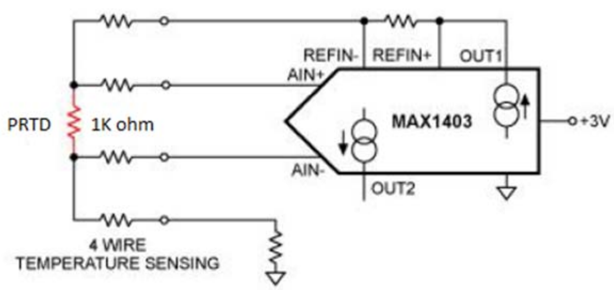

Fig. 1: 4-Wire temperature sensing with current excitation

Any suitable low noise ADC capable of performing conversion of differential voltage with high resolution and very low offset error voltage can be used to convert the analog voltage into digital value. The PRTD element PT1000 is excited with a 200µA current source. As an alternative to Fig. 1, Fig. 2 shows a cost effective 2-wire RTD temperature sensing circuit which can be used if the parasitic resistance is known and unchanging.

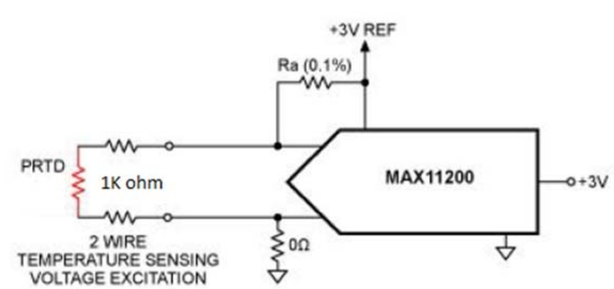

Fig. 2: 2-Wire temperature sensing with voltage excitation

This arrangement is used for the experiment done. Instead of a current source, a precision reference voltage source is used to excite the PRTD through a single precision resistor and the same reference voltage is used to provide the reference bias for the ADC. Low noise 24-bit ADC MAX11200 and PRTD PT1000 PTS1206 is used. The PRTD can be connected directly to the ADC because of its higher resistance. The ADC can measure the temperature accurately and ratiometrically.

Voltage across the RTD V_{RTD} is given by

$$V_{RTD} = V_{REF} \text{ x } (R_t/(R_a + R_t)) \quad \text{(Eq. 1)}$$

where V_{REF} is the ADC voltage reference, R_t is the resistance of PRTD at t °C, and R_a is the current limiting resistor.

In terms of ADC's output code A_{ADC} the voltage VRTD is given by

$$V_{RTD} = V_{REF} \text{ x } (A_{ADC}/FS) \quad \text{Eq. 2)}$$

where FS is the full scale code of the ADC. In case of ADC MAX11200 FS = $2^{23} - 1$, since it is a 24-bit ADC.

Combining equation (1) and (2) we have

$$R_t = R_a \text{ x } (A_{ADC}/(FS - A_{ADC})) - \quad \text{(Eq. 3)}$$

Equation 3 shows that there is a change in ADC output with change in resistance of the PRTD which is in proportion to change in temperature. The Microcontroller can read the ADC output A_{ADC} and calculate the temperature t.

5. PRTD ERROR ANALYSIS

5.1. Error due to lead-wire resistance

The length of the 22AWG(American Wire Gauge) copper wire that is used in Fig. 2 is 3 feet. Its resistance per foot at 25°C is 0.0161Ω. The lead wire resistance is given by

$R_{W} = 2 \text{ x } 3 \text{ x } 0.0161 = 0.1\Omega$

The error in temperature due to the lead wire resistance T_{WER} is R_W /S, where S is the average PRTD sensitivity. For a PT1000 device S = 3.85Ω/°C. Therefore

T_{WER} = 0.1Ω/ 3.85Ω/°C = 0.026°C

According to IEC60751 standard it is one order of magnitude below the class F0.3 tolerance of ±0.30°C. This means that 3-feet two-wire configuration of PRTD can be used directly without any method of wire compensation.

5.2. Error due to PRTD self-heating

Excitation current that flows through the PRTD warms up the sensor that increases the sensor resistance above the level that it would otherwise assume due to the temperature being measured. This introduces the error due to self-Heating. Excitation current also produces the voltage drop across the sensor to be measured by the ADC. It must be as high as practical to ensure that it remains above the ADC's voltage noise level. The thermal error T_{err} is given by

$T_{err} = I_{ext}^2 \times R_t \times K_{tpack}$ ------- (Eq. 4)

where I_{ext} is the excitation current, K_{tpack} is the RTD self-heating error coefficient (0.7°C /mW).

Table 2 shows some calculated values of thermal error T_{err} given by equation 4 at temperatures between -55°C and 155°C corresponding to experimental set-up shown in Fig. 2. R_t is calculated from equation 3 for different values of temperatures at which the A_{ADC} values read by the microcontroller are recorded.

Table 2: Thermal error calculation

PT1000, R_a=27000Ω			
Temperature	***I_{ext} (µA)***	***R_t (Ω)***	***T_{err}(°C)***
-55°C	108	783	0.013
0°C	107	1000	0.016
20°C	106	1077	0.018
155°C	104	1591	0.025

So, it is seen from table 2 that the thermal error **T_{err} is maximum of 0.025°C** which is below the class F0.3 tolerance of ±0.3°C. Its excitation current of 108µA is also comparatively less and therefore PT1000 is preferable for low power instrumentation applications. R_a resistors should be of metal-film type of ±0.1% or better tolerances and ¼ power rating, and a low temperature coefficient.

5.3. Linearity error of PRTD PT1000

A linear approximation of the PRTD device can be made by calculating the PRTD resistance over a temperature range of -20°C to 100°C using equation 5:

$R_t = R_0 (1 + T \times a)$ -- (Eq. 5)

where R_t is the resistance of the PT1000 at T°C, R_0 is the resistance of the PT1000 at 0°C and a= 0.00385 Ω/ Ω/ °C is the mean temperature coefficient at temperature between -20°C to 100°C. Table 3 shows some readings of linearity error corresponding to experimental set-up shown in Fig. 2.

Table 3: Linearity error calculation

V_{REF} = 3V, PT1000, R_a=27000Ω					
Temperature	R_t (Ω)	$R_{t\,(nom)}$(Ω)	V_{RTD} (V)	ADC code	Err
-20°C	923	921.6	0.099	277286	0.15
-10°C	961.5	960.9	0.103	288454	0.06
0°C	1000	1000	0.107	299592	0.00
10°C	1038.5	1039	0.111	310699	-0.05
20°C	1077	1077.9	0.115	321776	-0.08
30°C	1115.5	1116.7	0.119	332822	-0.11
40°C	1154	1155.4	0.122	343838	-0.12
60°C	1231	1232.4	0.130	365780	-0.11
100°C	1385	1385	0.146	409308	0.00

In table 3, R_t is calculated from equation 5. $R_{t\,(nom)}$ is given by the PRTD device manufacturers specification document. V_{RTD} is calculated from equation 2 and A_{ADC} is the ADC code as read by the microcontroller. As seen from table 3 the **linearization error for the stated temperature range are all within ±0.15%**, which is better than the class F0.3 tolerance (±0.3°C). With the values of A_{ADC} that is obtained by the microcontroller R_t is also calculated from equation 3 and the practical measurements done also confirms that the digital representation of the temperature-reading errors also remain within the class F0.3 tolerance (±0.3°C).

6. PRTD TEMPERATURE MEASUREMENT FOR WIDER RANGE

To measure temperature between -20°C to 100°C equation 3 and 5 can be implemented in the firmware of a microcontroller based temperature measurement system using PT1000 PRTD sensing element to measure temperature with much improved accuracy. For increasing the range between 0°C to +800°C, the linearization equation requires two coefficients as given by equation 6:

$R_t = R_0 (1 + a \times T + b \times T^2)$ -(Eq. 6)

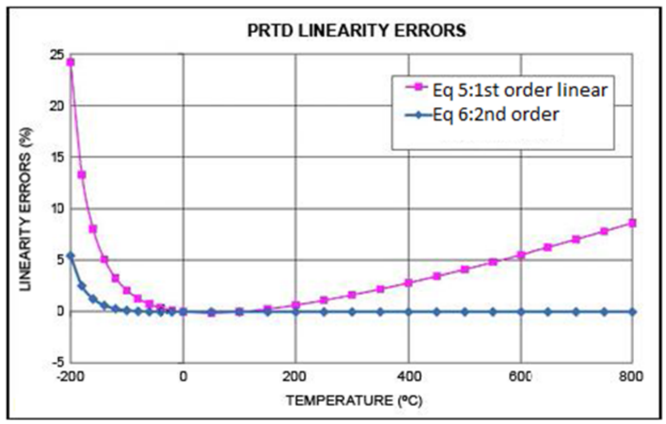

Fig. 3: PRTD Linearity error

It is seen from Fig. 3 that for temperature range beyond 200°C and below 0°C the linearity error increases if 1st order equation 5 is used to calculate temperature. The error can be minimized to a negligible value if the 2nd order equation 6 is used beyond 200°C and works considerably well up to 800°C.

For lower temperature range between -200°C to 0°C, linearization equation requires three coefficients as given by equation 7:

$R_t = R_0 [1 + a \times T + b \times T^2 + (T\text{-}100)\, C \times T^3]$ -- -(Eq. 7)

Where a, b and c are temperature coefficients as given by the PRTD device datasheet.

Equation 3 can be used by the microcontroller firmware to calculate R_t(PRTD resistance) for any given temperature T, and then using any one equation out of 5 or 6 or 7 depending upon the temperature range, temperature T can be found out by the microcontroller firmware accurately.

7. MICROCONTROLLER TEMPERATURE MEASUREMENT SYSTEM

A simple scheme is proposed to implement the temperature measurement system using a 8-bit Freescale semiconductor microcontroller MC9S08JM60.

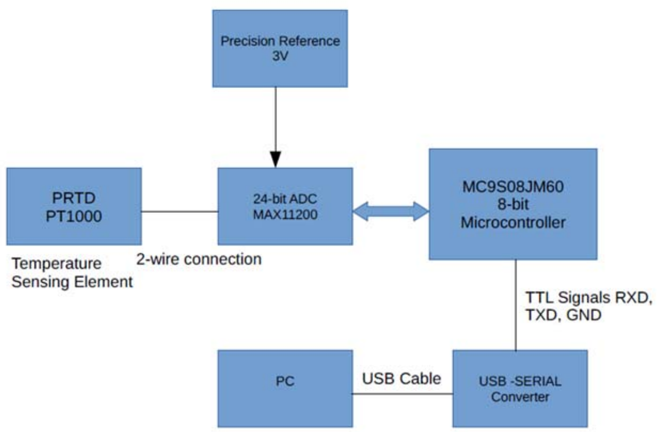

Fig. 4: Microcontroller based temperature measurement system

Above circuit that uses the ADC of 24 bit and PRTD PT1000 has a PRTD resolution of 0.000926°C/LSB and a noise-free resolution of 0.0073°C/NFR for a temperature range of -55°C to 155°C. NFR is the minimum temperature value that can be differentiated by the ADC. This allows a better temperature resolution than 0.05°C within the given range of -55°C to 155°C which is more than sufficient for most industrial and medical applications.

8. CONCLUSION

PRTD device can be used as the sensing element for a variety of high accuracy and precision temperature measurement applications. Appropriate ADC that has a high resolution and low-noise reference voltage need to be used. Together the ADC, PRTD 1000 and the microcontroller provide a temperature measurement system that is ideal for portable temperature sensing applications for wider range and higher accuracy. The linearity error of the PRTD sensing device for higher temperature and very low temperature can be minimized to a negligible value by the implementation of mathematical expressions in the microcontroller firmware. It provides a high performance and cost-effective temperature measurement solution. It eliminates the need of using an additional instrumentation amplifier and lesser wiring and lower thermal error further reduce the system cost and complexity.

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