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Precision RTD Instrumentation for Temperature Sensing

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INTRODUCTION

Precision RTD (Resistive Temperature Detector) instrumentation is key for high performance thermal management applications. This application note shows how to use a high resolution Delta-Sigma Analog-to-Digital converter, and two resistors to measure RTD resistance ratiometrically. A ±0.1°C accuracy and ±0.01°C measurement resolution can be achieved across the RTD temperature range of -200°C to +800°C with a single point calibration.

A high resolution Delta-Sigma ADC can serve well for high performance thermal management applications such as industrial or medical instrumentation. Traditionally, RTDs are biased with a constant current source. The voltage drop across the RTD is conditioned using an Instrumentation Amplifier which requires multiple resistors, capacitors and few operation amplifiers and/or a stand-alone instrumentation amplifier. This analog instrumentation technique requires a low noise and stable system to calibrate and accurately measure temperature. It also requires an operator for optimization on the production floor. With the Delta-Sigma ADC solution, the RTD is directly connected to the ADC (Microchip's MCP3551 family of 22 bit Delta-Sigma ADCs) and a single low tolerance resistor is used to bias the RTD from the ADC reference voltage (Figure 1) and accurately measure temperature ratiometrically. A low drop out linear regulator (LDO) is used to provide a reference voltage.

SOLUTION

This solution uses a common reference voltage to bias the RTD and the ADC which provides a ratio-metric relation between the ADC resolution and the RTD temperature resolution. Only one biasing resistor, R_A, is needed to set the measurement resolution ratio (Equation 1).

EQUATION 1: RTD RESISTANCE

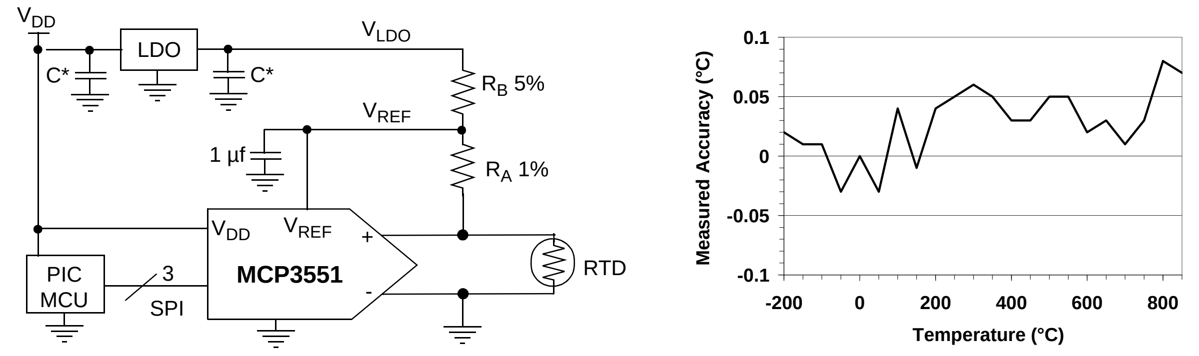
$$R_{RTD} = R_A\left(\frac{Code}{2^{n-1} - Code}\right)$$

Where:

Code = ADC output code
R_A = Biasing resistor
n = ADC number of bits (22 bits with sign, MCP3551)

For instance, a 2V ADC reference voltage (V_{REF}) results in a 1 µV/LSb (Least Significant Bit) resolution. Setting R_A = R_B = 6.8 kΩ provides 111.6 µV/°C temperature coefficient (PT100 RTD with 0.385Ω/°C temperature coefficient). This provides 0.008°C/LSb temperature measurement resolution for the entire range of 20Ω to 320Ω or -200°C to +800°C. A single point calibration with a 0.1% 100Ω resistor provides ±0.1°C accuracy as shown in Figure 1.

This approach provides a plug-and-play solution with minimum adjustment. However, the system accuracy depends on several factors such as the RTD type, biasing circuit tolerance and stability, error due to power dissipation or self-heat, and RTD non-linear characteristics.



* See LDO Data Sheet

FIGURE 1: *RTD Instrumentation Circuit Block Diagram and Output Performance [3].*

Ratiometric Measurement

The key feature of a ratiometric measurement technique is that the temperature accuracy does not depend on an accurate reference voltage. The ADC reference voltage varies with respect to change in RTD resistance due to the voltage divider relation (Equation 2). This measurement maintains constrant resolution. It eliminates the need for a constant biasing current source or a voltage source, which can be costly, while providing a highly accurate temperature measurement solution. Figure 2 shows circuit block diagram with the ADC reference.

EQUATION 2: REFERENCE VOLTAGE

$$V_{REF} = \frac{R_A + R_{RTD}}{R_A + R_B + R_{RTD}}$$

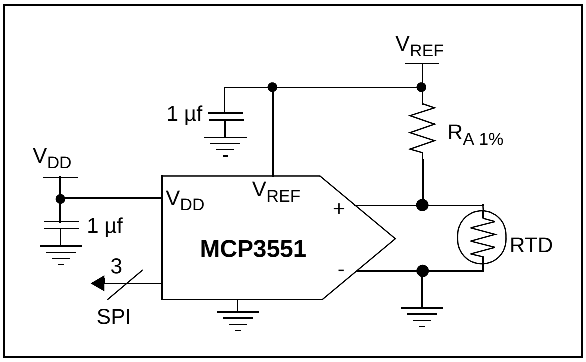


FIGURE 2: RTD Biasing Circuit.

R_A and R_B must be sufficiently large to minimize error due to selfheat while providing adequate measurement resolution.

Equation 3 and Equation 4 show that due to the ratiometric relation V_{REF} and R_B cancel. They do not influence the code to RTD-resistance conversion. This equation can be easily implemented using a 16-bit microcontroller such as PIC18F family.

EQUATION 3: VOLTAGE ACROSS RTD

$$V_{RTD} = V_{REF}\left(\frac{R_{RTD}}{R_A + R_{RTD}}\right) = V_{REF}\left(\frac{Code}{2^{n-1}}\right)$$

Where:

V_{RTD} (V) = RTD voltage
V_{REF} (V) = Reference Voltage
Code = ADC output code
n = ADC number of bits (22 bits with sign, MCP3551)

Solving for R_{RTD} from Equation 3 gives:

EQUATION 4: RTD RESISTANCE AND ADC CODE RELATIONS

$$R_{RTD} = R_A\left(\frac{Code}{2^{n-1} - Code}\right)$$

Measurement Resolution and ADC Characteristics

EQUATION 5: ADC RESOLUTION

$$ADC_{RESOLUTION} = \frac{V_{REF}}{2^{(n-1)}}$$

Where:

V_{REF}(V) = Reference Voltage
n = ADC number of bits (22 bits with sign, MCP3551)

The key element to this solution is the direct proportionality of ΔADC_{LSb_quanta} and ΔR_{RTD}. The temperature measurement resolution can be determined as shown in Equation 6.

EQUATION 6: TEMPERATURE MEASUREMENT RESOLUTION

$$T_{RES} = \frac{ADC_{RESOLUTION}}{\Delta V_{RTD}}$$

Where:

T_{RES} (°C/LSb) = Temperature Measurement Resolution

When $R_A = R_B = 6800\Omega$, the bias current is ~290 µA. This provides < 0.01°C/LSb temperature resolution. As the RTD resistance varies due to temperature, the I_{BIAS} (biasing current) varies and temperature resolution remains below 0.01°C/LSb as shown in Figure 3.

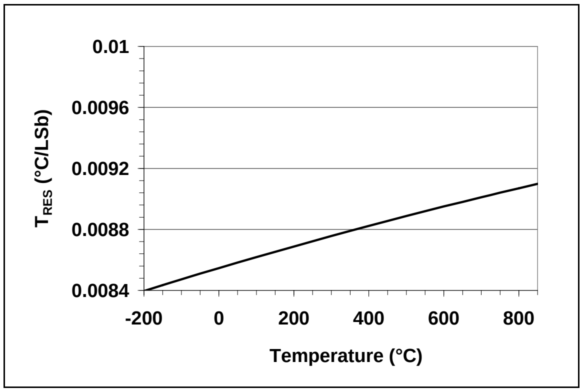


FIGURE 3: T_{RES} vs. RTD Resistance.

The MCP3551 22-bit differential ADC characteristics is optimum for this type of application. There are few specifications that must be carefully considered, such as conversion accuracy and noise performance. The maximum full scale error of the MCP3551 is 10 ppm and the error drift is 0.028 ppm/C. The maximum Intergral Non-linearity is 6 ppm. These specifications are so minute when considering the overall effect to temperature measurement accuracy. If I_{BIAS} is set to ~300 µA, then the input voltage range to the ADC is ~100 mV (V_{RTD}) over the entire RTD temperature range. Therefore, the error is much less than the full scale error specified in the ADC datasheet.

However, the input offset noise is 2.5 µV (typical) and 6 µV (typical) for MCP3551 and MCP3553 ADCs, respectively. This specification adds offset error that needs be considered when converting temperature. The offset error is specified as 12 µV (maximum) at +25°C. This means there is up to 12 LSb flicker or the temperature measurement precision is 0.09°C maximum (Equation 6). This can be improved by taking the average of multiple samples to precisely determine temperature.

R_A Tolerance and Measurement Accuracy

The variation in R_A characteristics introduces temperature accuracy error. A 1% tolerance in R_A produces a 20°C error and a 0.1% tolerance produces a 2°C error. For lower tolerance resistors, R_A must be calibrated for precision temperature measurements.

In order to precisely calibrate R_A, a calibration resistor can be used in place of the RTD, such as 100Ω 0.1% tolerance resistor and Equation 4 can be rearranged to determine R_A.

RTD Temperature Calculation

RTDs are significantly non-linear. Depending on the RTD type and specification, the resistor to temperature conversion equations have been defined and standardized. The equation for the PT100 RTD can be found at American Society for Testing and Materials (ASTM) [1] specification number E1137E.

Figure 4 shows the error that occurs by ignoring the 2nd and higher power errors from RTD.

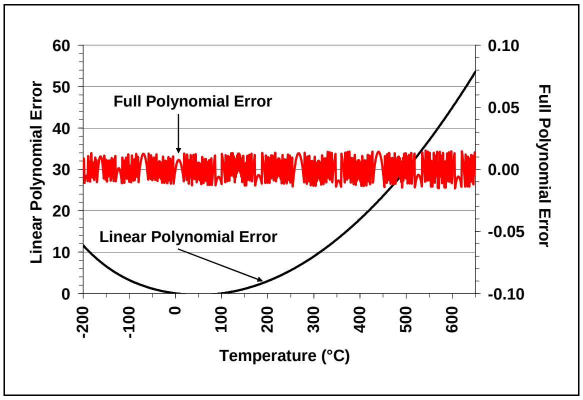


FIGURE 4: RTD to Temperature Conversion Error.

Power Supply Noise

Another source of error is the system power supply. Most power supplies for portable systems use switching regulators which generates high frequency glitches at the switching frequency of typically 100 kHz. Other sources of noise include digital switching from system processor or system oscillator. This high frequency noise can couple throughout system and directly influence the measurement accuracy. Therefore, high performance sensor applications require analog filters.

The power supply voltage, V_{DD}, connected to the input of the LDO must be filtered using Resistor Capacitor network (RC network) with low corner frequency, approximately 1 kHz. The filtered voltage can be set to a desired level using a low dropout linear regulator (LDO). Refer to the LDO datasheet for dropout voltage specification when setting the LDO output voltage. Figure 1 show a typical configuration. The two RC filters provide 40 dB per decade rolloff.

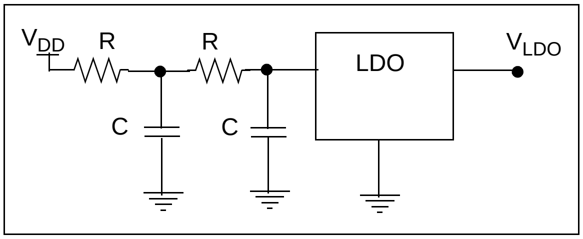


FIGURE 5: RTD Biasing Circuit.

Note that the RC filter is applied before the LDO. Typically, the Power Supply Rejection Ratio (PRSS) of an LDO is ~0 dB at higher frequencies. Therefore, It is necessary to filter the input voltage to prevent the noise coupling through the LDO to the ADC and RTD.

In addition, when designing PCB layout, avoid placing digital signal traces in close proximity to the RTD biasing circuit.

Effect of RTD Self-heat Due to Power Dissipation

When biasing RTD, self-heat due to power dissipation can compromise system accuracy. The effect of Self-heat can be reduced by reducing the biasing current magnitude. The current magnitude needs to be sufficiently low to reduce self-heat while providing adequate voltage range and measurement resolution. Ideally, the added temperature due to self-heat must be lower than the temperature measurement resolution, T_{RES} (Equation 6).

To determine error due to self-heat, refer to the RTD datasheet for Self-heat coefficient specification in degree Celsius per milli-watt (°C/mW). This coefficient is used to convert heat due to power dissipation to temperature. For example, a small surface mount PT100 RTD with 0.2°C/mW self-heat coefficient would dissipate 0.002°C with 300 µA bias current at 0°C (100Ω), and 0.006°C at high temperature (350Ω). In this case, the maximum heat dissipated due to self-heat is less then 0.008°C T_{RES}. Therefore, error due to self heat is not measurable.

EQUATION 7: RTD POWER

$$P_{RTD} = \frac{V_{RTD}}{R_{RTD}}$$

Where:

P_{RTD} (Watt) = Power across RTD

Test Result

This approach was validated using Microchip's MCP3551 ADC device [3] as shown in Figure 1.

The ratiomatric solution was used with a calibrated RTD simulator [4] to generate the data as shown in Table 1. The graph in Figure 1 shows that the ratiometric relation provides the highest accuracy.

TABLE 1: RATIOMETRIC TEST RESULTS USING AN RTD SIMULATOR

Ratiometric Measurement				
Temperature (°C)	**Resistance (Ω)**		**Measured Temperature – Full Polynomial (°C)**	**Measurement Error (°C)**
	Actual	**Measured**		
-200	18.52	18.51	-200.02	0.02
-150	39.72	39.72	-150.01	0.01
-100	60.26	60.25	-100.01	0.01
-50	80.31	80.32	-49.97	-0.03
0	100	100	0	0
50	119.4	119.41	50.03	-0.03
100	138.51	138.49	99.96	0.04
150	157.33	157.33	150.01	-0.01
200	175.86	175.84	199.96	0.04
250	194.1	194.08	249.95	0.05
300	212.05	212.03	299.94	0.06
350	229.72	229.7	349.95	0.05
400	247.09	247.08	399.97	0.03
450	264.18	264.17	449.97	0.03
500	280.98	280.96	499.95	0.05
550	297.49	297.47	549.95	0.05
600	313.71	313.7	599.98	0.02
650	329.64	329.61	649.97	0.03
700	345.28	345.28	699.99	0.01
750	360.64	360.6	749.97	0.03
800	375.7	375.68	799.92	0.08
850	390.48	390.45	849.93	0.07

CONCLUSION

Microchip’s MCP3551 differential ADC is ideal for high performance thermal management applications. This application note discusses an RTD application which uses a ratiometric relation between the ADC LSb quanta and the RTD temperature coefficient. This was achieved using low tolerance resistor and a reference voltage to bias the RTD and ADC and measure temperature ratiometrically with 0.01°C temperature resolution from -200°C to 800°C temperature range. A 0.1°C accuracy can be achieved using a single point calibration.

This approach eliminates the need for a high-performance RTD systems that require constant current source and complex instrumentation systems. This technique provides a low cost, high performance, plug and play solution for all RTDs.

REFERENCE

1. www.astm.com
2. National Institutes of Standards and Technology (NIST)
3. RTD Demonstration Board
   (estimated release in June 2008)
4. OMEGA RTD Simulator, CL510-7.
5. MCP3550/1/3 Data Sheet, *“Low-Power Single Channel 22-Bit Delta Sigma ADCs“,* DS21950, ©2007, Microchip Technology Inc.

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