Precision Temperature Sensing

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Temperature sensing forms an integral part of any industrial monitoring system. It is a widely used parameter in any given process controlled environment. Some of the common sensors used for measurement of absolute temperature or change in temperature are resistance temperature detectors (RTDs), diodes, thermistors, and thermocouples.

In this article, we will go through the points to be taken care while implementing precision temperature measurement system using these sensors. Temperature sensing involves selection of right sensors as well as necessary signal conditioning and digitization in order to efficiently and accurately measure the temperature. Before we go to the temperature measurement system, let’s examine the advantages and disadvantages of each of the commonly-used temperature sensor.

**Thermocouples**

Thermocouples work on the principle that the junction between two metals generates a voltage that is a function of temperature. A thermocouple consists of two pieces of dissimilar metals joined at one end which is called the hot junction. The other end which is called cold junction is connected to a measuring circuit. The difference in temperature between the hot and cold junctions causes an electromagnetic force (EMF) to develop. This EMF can be measured by the measurement circuit. Figure 1 shows a basic thermocouple circuit.

![Figure 1: Basic thermocouple circuit](image)

The actual voltage generated by the thermocouple depends on the temperature and the type of dissimilar metals used in the thermocouple. The sensitivity and temperature range of a thermocouple is dependent upon the metals used. There are numerous thermocouples available on the market which can be classified/distinguished based on the metals used; for example, type B (Platinum / Rhodium), type J (Iron / Constantan), and type K (Chromel / Alumel). One can be chosen based on the application’s requirements.

The primary advantages of thermocouples are their robustness, wide temperature range (-270 degree to 3000 degree), fast response, availability in several package types, and low cost. Looking at their limitations, they suffer from low accuracy and high noise.

**Resistance Temperature Detectors**

Resistance temperature detectors (RTD) works on the principle of change in electrical resistance in metals due to a change in temperature. Each metal has a specific and unique resistivity. The resistance of a metal is directly proportional to the length of the wire and inversely proportional to the cross-sectional area of the wire. The constant of proportionality is the resistivity coefficient of the wire.

The selection of metal for the construction of the RTD is a critical consideration in being able to measure temperature accurately. Metals used for the construction of RTDs are platinum, nickel, or copper. Of the three materials used in RTDs, platinum RTDs are the most accurate and reliable. They are also less susceptible to environmental contamination, which...
results in long term stability as well as repeatability. High temperature range (-250 degree to 900 degree), high accuracy, and linearity are the major advantages of RTDs. Their limitations include higher cost and slow responsiveness.

**Thermistors**

Similar to RTDs, thermistors also work on the same principle that resistance changes with temperature. However, thermistors generally have a negative temperature coefficient. The major advantages of thermistors are their low cost and reasonable accuracy. Their disadvantages can be identified as low temperature range and non-linearity. However, given that many of today’s microcontrollers have on-chip Flash, a lookup table can be maintained to mitigate linearity issues. If the temperature needs to be measured within -100 degree to 300 degree, thermistors can be used reliably for precision temperature measurement.

**Temperature Measurement Systems**

In any temperature monitoring system, a sensor must convert the temperature to an electrical signal which is then passed through a signal conditioning stage (the requirements vary based upon the sensor used), and onto an analog-to-digital converter (ADC). The system also needs communication peripherals to interface to other larger systems to provide feedback, as well as on-chip Flash memory for logging the values and some kind of display. Figure 2 shows the basic block diagram of a temperature measurement system.

![Figure 2: Block diagram of temperature measurement system](image)

Though Figure 2 shows signal conditioning before the ADC, there may be a need for post processing as well after converting the signal, depending upon whether the system is analog or digital. Overall accuracy is dependent upon the noise, offset, and gain error introduced in the pre-processing circuit and ADC. Data acquisition of temperature values from remote locations in real-time is a good feature in some of the applications like refineries, industries, and various automation. Serial communication protocols like UART, I2C are supported to transfer this data to a master system controller.

**Improving Thermocouple Accuracy**

Thermocouple-based systems are the most widely used for industrial control due to their huge temperature range. Here the EMF generated between junctions is measured to sense the temperature. It is assumed that the cold junction is at exactly zero degrees centigrade. However, maintaining a cold junction at this temperature is not practical in real applications. To achieve a precise measurement requires a technique known as cold junction compensation (CJC).

For CJC, a thermocouple-based precision temperature application is equipped with additional temperature sensor mounted at the tip of cold junction to measure the cold junction temperature. The most commonly-used sensor for cold junction temperature measurement is a thermistor due to its low cost and wide enough temperature range to cover cold junction temperatures for most applications. To measure the CJC voltage, first find the cold junction temperature and then check for the thermocouple EMF for that temperature. This is then added to the cold junction voltage, yielding the CJC voltage whose corresponding temperature is the actual value.
The EMF produced across a thermocouple measures only a few uVs, making it susceptible to noise. Also, before this signal is fed into the ADC, it needs to be amplified which also adds noise and offset. For precision measurement, this noise and offset should be removed. For the example system, let us see how to remove the offset and low frequency noise using correlated double sampling (CDS).

CDS reduces low frequency noise and offset in the signal processing stage. First the zero referenced offset is measured (to measure it, both inputs are shorted) and then the thermocouple voltage is measured. When the direct thermocouple signal is measured, it will include the actual thermocouple voltage, noise voltage, and offset (equation 1). The zero referenced reading includes noise and offset (equation 2).

\[ V_{\text{TCouple Signal}} = V_T + V_N + V_{\text{offset}} \]  
\[ V_{\text{Zero Ref}} = V_N + V_{\text{offset}} \]  

The previous zero referenced sample with respect to the current zero referenced measurement is:

\[ V_{\text{Zero ref Prev}} = (V_N + V_{\text{offset}})^{Z-1} \]  

The difference, then, between the current thermocouple measurement and the previous zero referenced signal is:

\[ V_{\text{signal}} = (V_T + V_N + V_{\text{offset}}) - (V_N + V_{\text{offset}})^{Z-1} \]  

\( V_{\text{offset}} \) is static, so its value on the current sample is the same as the value on the previous sample. \( V_N \) is not static as it is noise and so the drift term needs to be eliminated. Subtracting the previous noise term from the current sample will remove low frequency noise. Thus, CDS works as a high-pass filter.

The ADC itself has a low pass filter response removing high frequency noise. However, an IIR filter at the output of ADC will help to further attenuate the noise in the frequency range of transition or pass band of ADC. Mixed signal controllers available in markets are equipped with digital filters which can perform filtering in hardware instead of doing filtering in firmware and requiring CPU cycles. Figure 3 shows an implementation of a thermocouple-based temperature monitoring system using PSoC3 and PSoC5 devices from Cypress Semiconductors. These devices have an on-chip DelSig ADC with 20-bit resolution, built-in programmable gain buffer for signal amplification, and digital filter block (DFB) for filtering. It provides a highly integrated temperature measurement system. However, an additional gain stage may be needed based upon the thermocouple being used in the design. This gain can be given by an instrumentation amplifier which can be built using on-chip programmable gain amplifiers (PGA).
In the system shown in Figure 3, analog MUXes AMuxCDS and AMuxCDS_1 are used to switch the positive input of the ADC between the negative and positive terminal of the sensor output to implement correlated double sampling. Now the question would be, how to get the zero referenced count for both sensor circuits when the ADC used is the same. Here is the answer – both the thermistor and thermocouple have a different output voltage range and hence require different amounts of amplification. The ADC in PSoC3 and PSoC5 devices have multiple ADC configurations which can be changed at run-time. For different gain settings, the offset will be different and requires that CDS be implemented for both sensor circuits. It will help to remove the offset of the complete analog signal chain. AMux is used for sensor selection between the thermocouple and thermistor. DMA reads the ADC value and writes to the digital filter block (DFB) to filter the noise.

**RTDs and Thermistors**

Measuring temperature using an RTD and thermistor requires measuring resistance, and thus the way resistance is measured determines the accuracy of system. To measure any signal precisely, differential inputs should be used as opposed to single-ended inputs. Differential inputs eliminate the common mode noise and are good for uV sensitivity (compared to single-ended inputs which are good only for mV sensitivity). Let us look at two ways of connecting the –ve input to the ADC in differential mode as shown in Figure 4.
Figure 4: Two different ways to connect –ve input

The topology shown on the right figure 4 is better than the one on the left. In the circuit shown on right, the -ve signal is connected directly to the reference close to the resistor divider. The circuit shown on the right helps reduce the noise in the measurement and error due to PCB traces or wire resistance.

A temperature measurement system based on a thermistor is a superset of Figure 3 and 4 only. Now, let us look at the measurement system using RTD. A platinum RTD temperature sensing element is the most accurate and stable over time and temperature, thus making it the first choice in precision temperature measurement applications. The voltage drop across the RTD can be measured in the same way as across a thermistor, generally known as the 2-wire method. When the connection of the RTD to the measurement system is through long cables, the cable resistance becomes the major source of measurement error taken if a voltage source is used for excitation. Figure 5 gives the difference between 2-wire measurement and 4-wire measurement.

![Figure 5: 2-wire and 4-wire connections](image)

In a 2-wire circuit, the resistance of the RTD (RRTD) will be measured as per equation 5. However, if we look at the circuit, there is another resistance, Rwire, that will cause an error in measurement:

\[ R_{RTD} = \frac{(R_{ref} + R_{wire}) (V_2 - V_1)}{(V - V_2)} \]  

On the other hand, the resistance of the RTD in a 4-wire measurement will be given by equation 6. As the measurement system has very high input impedance, no current flows in the measurement system and hence the resistance coming in series between the resistor divider nodes and measurement system does not matter. Equation 6 is derived by equating the current flowing through Rref and RTD resistance Rrtd.

\[ R_{RTD} = \frac{R_{ref} (V_2 - V_1)}{(V_4 - V_3)} \]  

Looking at equation 5 and 6, the accuracy of the measurement depends upon the accuracy of Rref. To overcome this issue in voltage excitation, RTDs are excited using a constant current source instead of a voltage source. While using a constant current source, the voltage drop across the RTD only depends upon its resistance and the value of the constant current source. However, the accuracy of the measurement using current excitation depends upon the accuracy of the current source. For precision measurements, the current DAC should be calibrated using a TIA. Figure 6 shows the possible implementation of an RTD-based temperature measurement system using PSoC3 and PSoC5 devices. These devices have on-chip current source that eliminates the need for another opamp-based analog circuit for generating the same. Also, these devices have on-chip TIA which can be used to calibrate the IDAC.
To summarize the major points to be considered for precision temperature measurement:
1. Select the appropriate sensor needed for the application.
2. CDS helps in making accurate sensor readings and avoiding offset errors while removing low frequency noise.
3. For thermocouple-based system, filters can be used to remove noise.
4. Current excitation helps to improve system accuracy by removing inaccurate reference resistance from the circuit.
5. If voltage excitation is used, a 4-wire measurement system should be used.
6. Overall accuracy of the system is decided by the accuracy and resolution of the signal chain. Therefore, a Delta sigma ADC with high accuracy and resolution is recommended.
7. For accommodating changes in designs with evolving requirements without compromising precision, a mixed-signal array-based implementation is recommended.

Temperature sensing forms an important part of many system industrial or embedded designs. We have discussed the various challenges in accurately reading sensor values and how one can use precision analog techniques to improve accuracy. General techniques involved can be equally applied to other sensor interface circuits as well.