Thermocouple Measurements without Custom Electronics

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ABSTRACT

Thermocouple measurements require "cold junction" compensation in order to obtain a correct reading. This compensation has traditionally been done with custom circuitry. In flight test applications where volume and power are at a premium (e.g. weapons flight test) it is desirable to have a more flexible solution that uses standard analog data acquisition channels already available as part of the encoder circuitry and performs compensation with remote software. This can be done via digital compensation, but certain measures must be taken to maintain accuracy and minimize noise. This paper describes some of these techniques and their performance trade-offs.

KEY WORDS

Thermocouple, Cold Junction, Compensation, Noise Correlation

INTRODUCTION

Thermocouples are commonly used for temperature measurements in flight test. Thermocouples can handle extremely wide temperature ranges, with different thermocouple types being characterized to handle temperatures as high as 1800°C and as low as three degrees above absolute zero. The construction of thermocouples (two pieces of wire) means that they have very low thermal mass and can withstand harsh mechanical environments. However, thermocouples also have some intrinsic error factors which must be controlled to obtain an accurate reading. Also thermocouples generate very small voltages and can be highly susceptible to corruption by environmental noise.

In flight test applications, thermocouple data is typically acquired using a customized data acquisition module which contains analog compensation circuitry to correct for measurement error sources in the thermocouple interface. While this solution serves many needs, it is desirable to find a solution which can be reached using standard data acquisition modules. Such a solution could decrease the overall size, weight, and power of the data acquisition unit, as well as making the overall data acquisition system more versatile and reconfigurable.

REVIEW OF THERMOCOUPLE BASICS

Thermocouples are temperature sensors which are formed by the junction of two different metals. The junction of the two metals will generate a temperature-dependent voltage, a phenomenon known as the Seebeck Effect. Typically thermocouples are comprised of a pair of wires with a connection at the end of the wire which generates the thermoelectric voltage. Different combinations of metals provide different responses (voltage versus temperature). Standard thermocouple types are given letter designations by the National Institute of Standards and Test. A representative diagram of a basic Type T thermocouple is shown in Figure 1.

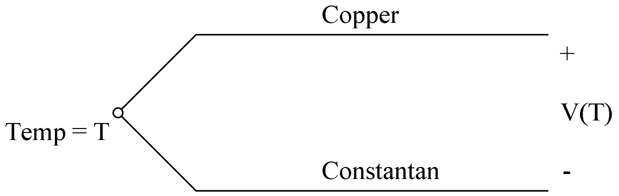

Figure 1 - A Type "T" Thermocouple

The thermoelectric voltages generated by the most commonly used thermocouples are very small, less than 100 microvolts per degree Celsius.

At some point the thermocouple must interface into the standard wiring of a data acquisition circuit, which is typically composed of copper. At this point the junction between the thermocouple wire metals and the standard copper wiring forms another parasitic thermocouple. As shown in Figure 2, this parasitic thermocouple is of the same type but with opposite polarity. Although the example in Figure 2 shows a thermocouple using copper as one of its metals, the same principle holds for any type of thermocouple as long as the two junctions to the copper wires are at equal temperatures.

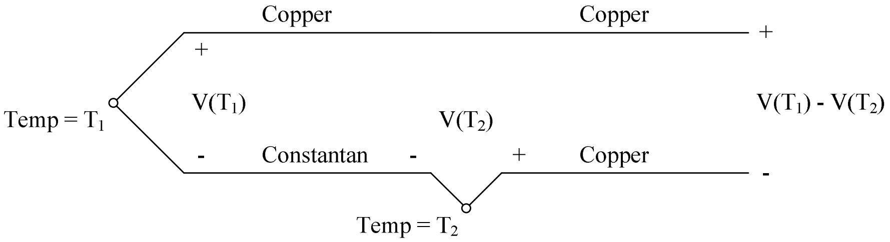

Figure 2 - Transition to copper forms a parasitic thermocouple

The parasitic thermocouple, which cannot be avoided, has the result that the voltage measured by the data acquisition circuitry is a function of both the temperature at the measurement point and the temperature at the parasitic thermocouple junction. In standard thermocouple applications this is known as the “cold junction” and its temperature is held at zero degrees Celsius. The standard ITS-90 reference functions for thermocouple voltage versus temperature are based on this assumption of a zero degree Celsius cold junction. However, in flight test applications it is typically not feasible to control the temperature of this junction. Because of this, the voltage introduced by this parasitic thermocouple cannot be known in advance; instead its voltage must be dynamically determined and a compensation algorithm used to correct for this voltage.

BASIC METHODS OF COMPENSATION

Dynamic correction for the parasitic thermocouple voltage can be accomplished by measuring the temperature of the parasitic junction as shown in Figure 3. The temperature of this junction can be measured using a device which provides an absolute temperature reading (as opposed to the relative temperature reading provided by the thermocouple). Devices such as a resistive temperature device (RTD) or the Analog Devices AD590 two terminal temperature transducer IC can be used for this purpose. Using the temperature determined by this sensor, the parasitic thermocouple voltage can be determined and corrected.

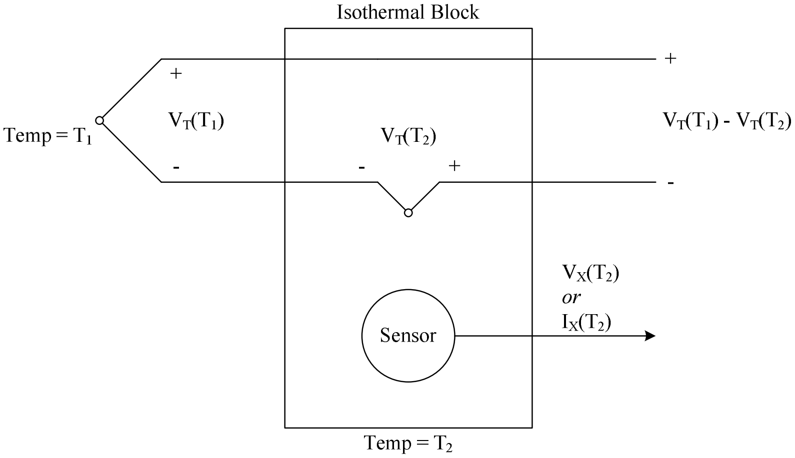

Figure 3 - Compensation by measuring parasitic thermocouple temperature

The standard means for performing this correction is to use an analog circuit. The voltage or current from the sensor is fed into a linear circuit, typically an op-amp, which generates an approximation of the thermocouple voltage. This voltage is added back into the thermocouple lines as shown in Figure 4. It should be noted that the accuracy of this compensation is dependent on the block being truly isothermal; any difference between the temperature of the sensor and the temperature of the parasitic thermocouple will contribute error into the final measurement.

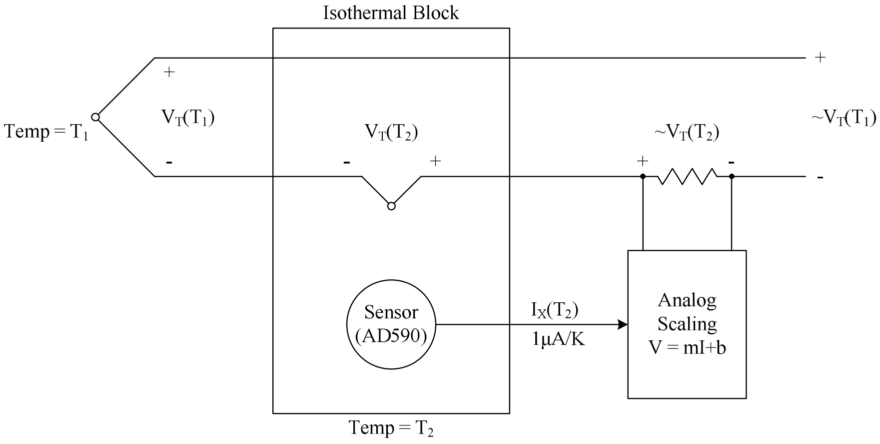

Figure 4 - Analog thermocouple compensation

In telemetry encoders and data acquisition units, the addition of this analog scaling circuitry requires a custom module. In applications where space is at a premium, it would be preferable to perform this compensation in the digital domain.

The analog compensation has the additional drawback of reduced accuracy. The voltage-versus temperature relationship of thermocouples is based on a highly nonlinear function. This relationship can be approximated via a linear function (which is typically known as the "Seebeck Coefficient"). However, as with any linear approximation, accuracy begins to degrade over wider ranges. As Figure 5 shows, the Seebeck Coefficient can vary widely over temperature, while a simple linear circuit can only generate a constant value. For certain thermocouple types such as Type E or Type T the Seebeck Coefficient deviates from its nominal (25°C) value by roughly +/- 10%, causing potential for significant error.

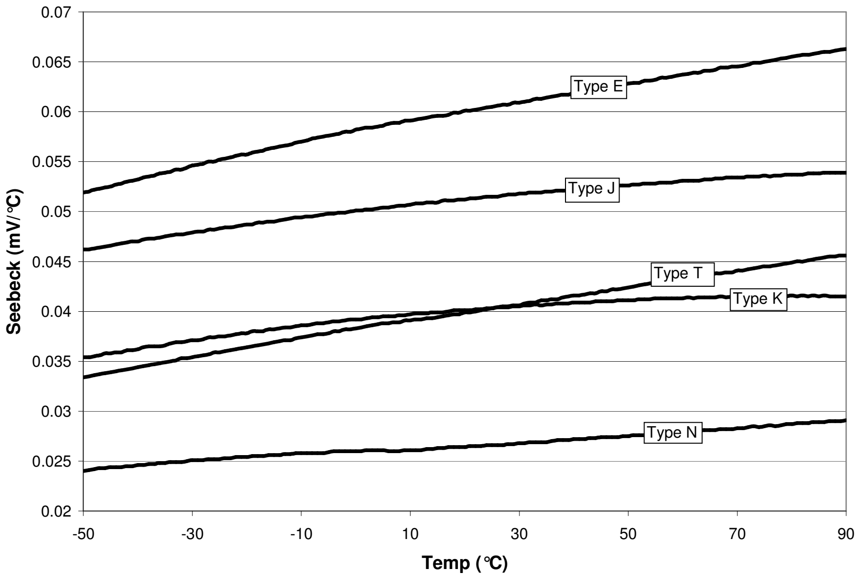

Figure 5 - Seebeck Coefficient vs temperature for various thermocouple types

DIGITAL COMPENSATION

A basic diagram of digital compensation is shown in Figure 6. Similar to the analog compensation scheme, the temperature of the parasitic thermocouple is measured. This temperature is used to determine the voltage contribution from the parasitic thermocouple. From this, the true voltage of the target thermocouple can be determined, and thus the temperature being measured.

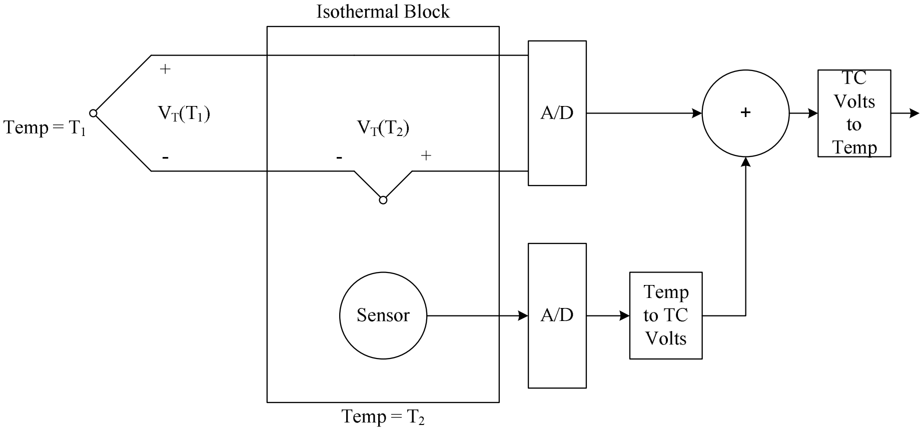

Figure 6 - Basic digital compensation

One benefit of this approach is that all steps after the A/D conversion can be performed within the vehicle or in remote data visualization equipment. The processing can be performed off-line, or in real-time. Another advantage is that the correction algorithm can use a higher-order function (much more easily than in an analog compensation circuit) for converting the junction temperature into thermocouple voltage, greatly reducing the error due to variation in the Seebeck coefficient as compared to the simple linear compensation approximations. One small disadvantage to this approach is the additional bandwidth required to transmit the cold junction data if digital compensation is performed remotely.

NOISE AND NOISE CANCELLATION

As previously mentioned, thermocouple measurements involve very low voltages and the construction of the thermocouple sensors (long strands of wire) makes them highly susceptible to environmental noise. The level of noise seen in the sensors is a function of system wiring and shielding, as well as the noise sources present in the system.

As shown in Figure 7, environmental noise will couple into all locations of the thermocouple wiring, both before and after the cold junction. In a typical installation, the wires between the cold junction and the data acquisition unit are tightly bundled together and so the two sets of wires will be subject to the same noise signals. Because of this, it is possible, depending on the wire arrangement and relative impedance of the various connections, for the noise signals on these two sets of wires to be highly correlated, with either positive or negative correlation.

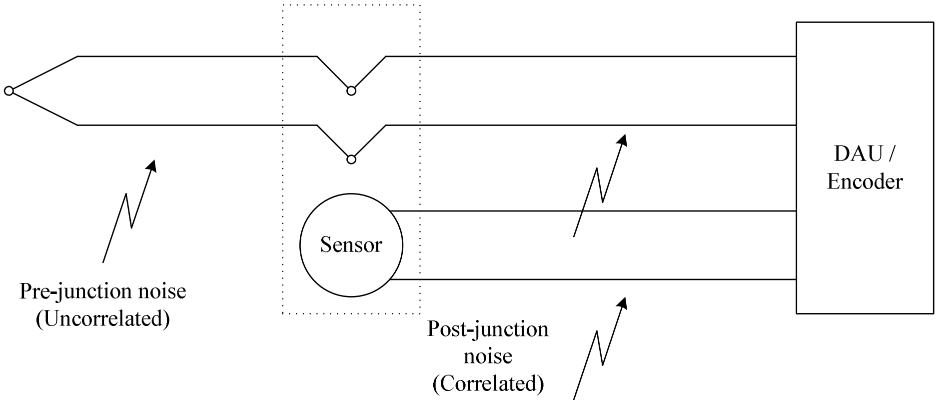

Figure 7 - Noise inputs into a thermocouple system

When the signals from the thermocouple and the cold junction measurement are added to form the compensated measurement, their component noise signals will be added as well. The RMS magnitude of the resultant noise sources depends on the degree of correlation as shown in the following equation:

$$E_{nT} = \sqrt{E_{n1}^2 + E_{n2}^2 + 2 \cdot C \cdot E_{n1} \cdot E_{n2}} \quad (1)$$

Where:

E_{nT} is the total RMS noise seen in the combined signal, in volts RMS

E_{n1} and E_{n2} are the RMS noise levels in the two respective inputs, in volts RMS, and

C is the coefficient of correlation between the two noise signals (dimensionless)

The correlation coefficient C can range from 0 (for completely uncorrelated) to +1 (full positive correlation) to -1 (full negative correlation). In a system that digitally samples both the thermocouple and cold junction signals, the timing of the digital sampling can be controlled to influence the correlation between the two signals.

If the analog noise signals seen on the two wires have a highly negative degree of correlation (C approaching -1), then the noise signals will tend to cancel each other out. In this situation, this high degree of correlation should be preserved by sampling the two signals simultaneously. However, if the two signals have a high degree of positive correlation (C approaching +1) then the added noise signals will reinforce each other, resulting in reduced system performance. In this situation, the sampling of the two signals can be staggered in time in order to reduce the degree of noise correlation seen in the sampled signals (lowering the value of C) and thereby reduce the resultant noise in the combined signal.

APPLICATION EXAMPLE

Digital sampling of the thermocouple and cold junction signals, with control over the relative sampling of the two sensors, can be accomplished with the L-3 Communications PCM330E telemetry encoder. The BCA310, an 8-channel analog module (7 differential inputs and one single-ended input), can be used to acquire the data; this module is user programmable to allow for multiple channels to be sampled simultaneously or staggered in time. The BCA310 module is typically intended for "bridge completion" applications and allows for various input resistors to be factory-installed in the module.

A typical PCM330E setup, using the BCA310 analog module, is illustrated in Figure 8. The target thermocouple is connected directly to one of the differential analog inputs. The AD590 cold junction sensor is connected to a second channel, which has one of the "bridge completion" resistors factory installed to convert the AD590 current-mode output into a voltage reading for the BCA310. The AD590 is powered by the excitation output of the channel. The excitation is user programmable; in this application an excitation voltage of 10V is suitable.

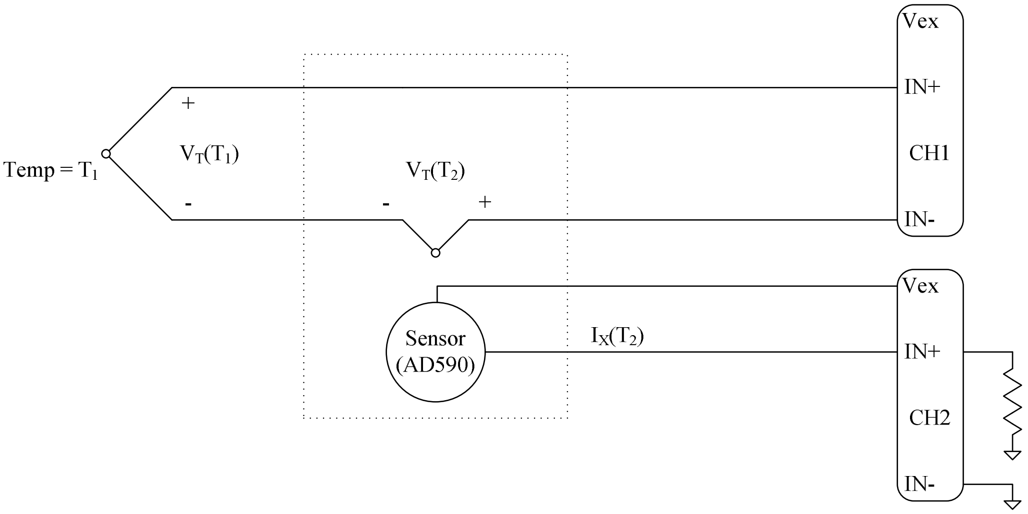

Figure 8 – Application Example with PCM330E (BCA310 analog module)

DIGITAL CORRECTION TECHNIQUES

A final concern when employing digital compensation for thermocouples is how to perform the conversion between thermocouple temperature and voltage. As Figure 6 illustrates, both the forward and inverse functions are required. The functions for translating between thermocouple voltage and temperature are highly complex; as shown in Table 1 they involve high-order polynomials. Certain thermocouple types also have transcendental functions (e^x) in their equations. Because of the complexity of these equations, direct computation of the thermocouple transfer functions in real time is generally not feasible.

Forward		Inverse	
From 270°C to 0°C	From 0°C to +400°C	From 270°C to 0°C (-5.603mV to 0mV)	From 0°C to +400°C (0mV to 20.872mV)
$0.387\,\mathrm{x}10^{-1}\ T\ +$	$0.387\,\mathrm{x}10^{-1}\ T\ +$	$2.595\,\mathrm{x}10^{1}\ V\ +$	$2.593\,\mathrm{x}10^{1}\ V\ +$
$0.442\,\mathrm{x}10^{-4}\ T^{2}\ +$	$0.333\,\mathrm{x}10^{-4}\ T^{2}\ +$	$-2.132\,\mathrm{x}10^{-1}\ V^{2}\ +$	$-7.603\,\mathrm{x}10^{-1}\ V^{2}\ +$
$0.118\,\mathrm{x}10^{-6}\ T^{3}\ +$	$0.206\,\mathrm{x}10^{-6}\ T^{3}\ +$	$7.902\,\mathrm{x}10^{-1}\ V^{3}\ +$	$4.638\,\mathrm{x}10^{-2}\ V^{3}\ +$
$0.200\,\mathrm{x}10^{-7}\ T^{4}\ +$	$-0.219\,\mathrm{x}10^{-8}\ T^{4}\ +$	$4.253\,\mathrm{x}10^{-1}\ V^{4}\ +$	$-2.165\,\mathrm{x}10^{-3}\ V^{4}\ +$
$0.901\,\mathrm{x}10^{-9}\ T^{5}\ +$	$0.110\,\mathrm{x}10^{-10}\ T^{5}\ +$	$1.330\,\mathrm{x}10^{-1}\ V^{5}\ +$	$6.048\,\mathrm{x}10^{-5}\ V^{5}\ +$
$0.227\,\mathrm{x}10^{-10}\ T^{6}\ +$	$-0.308\,\mathrm{x}10^{-13}\ T^{6}\ +$	$2.024\,\mathrm{x}10^{-2}\ V^{6}\ +$	$7.293\,\mathrm{x}10^{-7}\ V^{6}$
$0.361\,\mathrm{x}10^{-12}\ T^{7}\ +$	$0.455\,\mathrm{x}10^{-16}\ T^{7}\ +$	$1.267\,\mathrm{x}10^{-3}\ V^{7}$	
$0.385\,\mathrm{x}10^{-14}\ T^{8}\ +$	$-0.275\,\mathrm{x}10^{-19}\ T^{8}$		
$0.282\,\mathrm{x}10^{-16}\ T^{9}\ +$			
$0.143\,\mathrm{x}10^{-18}\ T^{10}\ +$			
$0.488\,\mathrm{x}10^{-21}\ T^{11}\ +$			
$0.108\,\mathrm{x}10^{-23}\ T^{12}\ +$			
$0.139\,\mathrm{x}10^{-26}\ T^{13}\ +$			
$0.798\,\mathrm{x}10^{-30}\ T^{14}$			

Table 1 – Forward and inverse ITS-90 polynomials for Type T thermocouple

Much of the literature currently available on digital thermocouple compensation recommends the use of a mathematical formula for thermocouple correction. For real-time processing, most digital compensation schemes rely upon some kind of approximation to avoid the complexity of calculating the general equations. The simplest approximation is the Seebeck coefficient (i.e. a linear best fit) as described above. For more accuracy, some schemes employ a piece-wise linear fit that calculates different linear approximations over various temperature ranges.

However, with modern hardware the scheme that is most accurate, computationally simple, and straightforward to implement is a simple look-up table. In typical flight test applications, analog parameters are typically sampled with 12-bit resolution, which means that there are only 2^{12} or 4096 discrete values that can be obtained from the measurement. Implementing a 4096-sample lookup table is easily within the capability of modern telemetry processing hardware and allows for quick computation with guaranteed accuracy.

Figure 9 shows a simple schematic diagram of thermocouple compensation using look-up tables. The cold junction voltage (or current) is first converted to its temperature, then to the equivalent thermocouple voltage. As the surrounding box indicates, these two conversions may easily be combined into a single 4096-sample look-up table. This derived thermocouple voltage (voltage of the parasitic thermocouple) is then added to the voltage measured at the main thermocouple. The resultant voltage number is the true voltage as seen at the target thermocouple, which is a 13-bit number (due to the addition of two 12-bit numbers). This voltage then may be converted to temperature via one more look-up table, this time with 8192 samples to accommodate all possible 13-bit numbers. Thus, the overall compensation can be accomplished with one 4096-sample look-up table, a 12-bit adder, and an 8192-sample look-up table.

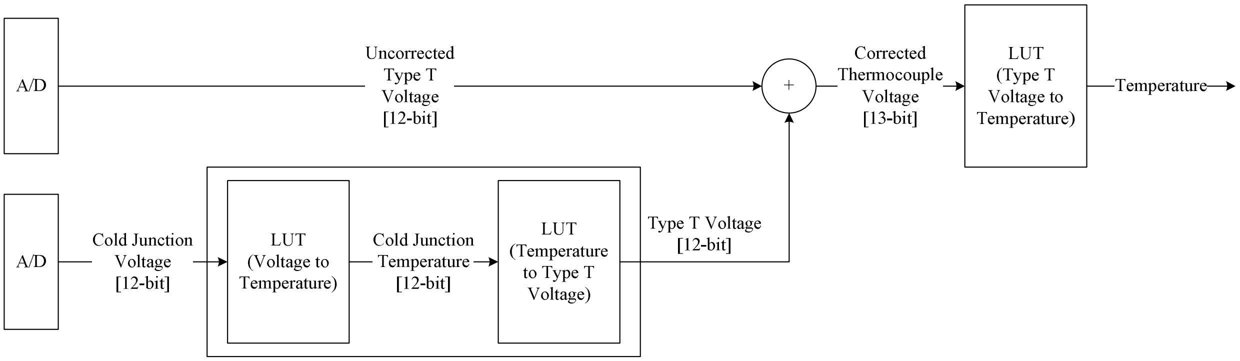

Figure 9 - Digital compensation based on look-up tables

In modern telemetry processing hardware the addition and look-up table functions would consume a minimal amount of the available resources, and both functions are computationally primitive so their loading on the host processor will be minimal. As a result, the digital compensation can be preformed in the data receiving hardware, eliminating the need to customize the encoder hardware or software to perform this correction.

CONCLUSION

While thermocouple measurements are typically acquired using custom circuitry, it is possible to obtain equal or better accuracy and noise performance using standard analog acquisition hardware and digital post-processing. This approach can reduce the size, weight, and power of the overall data acquisition system. By digitally sampling both the thermocouple sensor and its cold junction compensation circuitry, the relative sampling of the two can be controlled to provide the best noise performance. Direct computation of the thermocouple correction and the final measured temperature is highly complex, but through the use of look-up tables the computations can be performed in advance resulting in a high-speed system. The result is a flexible and highly efficient data acquisition solution.

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