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MEASUREMENT OF TEMPERATURE USING THERMOCOUPLE AND SOFTWARE SIGNAL CONDITIONING USING LABVIEW

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***Abstract*--Temperature is a measure of average kinetic energy of the particles in a sample of matter. The measurement of temperature using the thermocouple includes the signal conditioning stages of reference temperature sensor for Cold Junction Compensation, high amplification and linearization. Implementing the signal conditioning stages in the FPGA based embedded hardware increases the data acquisition rate. The proposed work includes measuring the temperature using the thermocouple & software signal conditioning and identifying the errors in the amplification, ADC count and linearization.The voltage of thermocouples varies non-linearly with change in temperature. The data acquisition process is carried out by using NI 9211 Thermocouple module along with carrier NI 9162.**

Keywords: Cold Junction Compensation, High amplification, Linearization, Software signal conditioning, ADC count.

I. INTRODUCTION

A thermocouple is a device made of two dissimilar conductors or semiconductors that contact each other at one or more points. Voltage is produced in the Thermocouple when the temperature of one of the contact points differs from the temperature of another, which is known as the thermoelectric effect. It is a major type of temperature sensor used for measurement and control purpose, and also converts a temperature gradient into electricity. Based on Seebeck's principle, thermocouples can measure only temperature differences and they need a known reference temperature to yield the absolute readings. The Seebeck effect describes the voltage or Electromotive Force (EMF) induced by the temperature gradient along the wire. The change in material EMF with respect to a change in temperature is called the Seebeck coefficient or thermoelectric sensitivity. This coefficient is usually a non-linear function of temperature.

For small changes in temperature over the length of a conductor, the voltage is approximately linear, which is represented by (1) where ΔV is the change in voltage, S is the Seebeck coefficient, and ΔT is the change in temperature:

$$\Delta V = S\Delta T \qquad (1)$$

Thermocouples require some form of temperature reference to compensate for the cold junctions. The most common method is to measure the temperature at the reference junction with a direct-reading temperature sensor then apply this cold-junction temperature measurement to the voltage reading to determine the temperature measured by the thermocouple. This process is called Cold-Junction Compensation (CJC). Because the purpose of CJC is to compensate for the known temperature of the cold junction, another less-common method is forcing the junction from the thermocouple metal to copper metal to a known temperature, such as 0 ºC, by submersing the junction in an ice-bath, and then connecting the copper wire from each junction to a voltage measurement device.

Data AcQuisition is the process of measurement of an electrical or physical phenomenon such as voltage, current, temperature, pressure, or sound with a computer[2]. PC-based DAQ systems exploit the processing power, productivity, and display of industry-standard computers that provides more powerful, flexible, and cost-effective measurement solution. When dealing with the factors like high voltages, noisy environments, extreme high and low signals, or simultaneous signal measurement, signal conditioning is the most essential process for an effective data acquisition system. It maximizes the accuracy of a system, and allows sensors to operate properly, and guarantees safety.

Static and Dynamic Temperature Measurements[1] were done earlier and it was found that a time constant of about 0.01 would be a good choice for use with the digital filter. This experiment was conducted in order to test the sensitivity of a J-type thermocouple, and also to test its dynamic response to a known step input. The sensitivity of the thermocouple was found by plotting its voltage vs. the temperature of the water it was submerged in. The sensitivity of the thermocouple was found to be 9.8728 mV/ºC. The time constant was found by quickly submerging the thermocouple in boiling water. The average time constant was 0.01464 seconds.

II. PROPOSED WORK

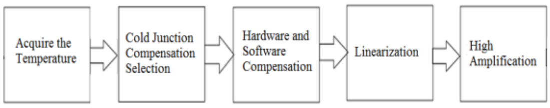


Fig.1.Block diagram of temperature measurement and signal conditioning of Thermocouple

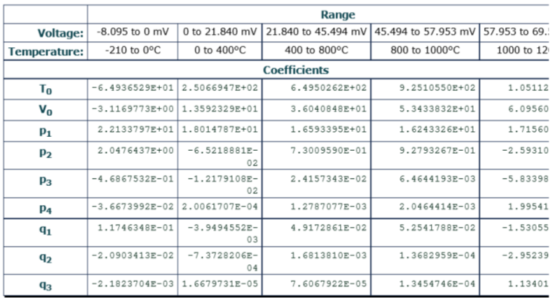
The Fig.1.illustrates the process flow for measuring the thermocouple temperature. The hot Temperature where two dissimilar metals contact each other, is first acquired from the sensor using the DAQ device. The reference Cold Junction Temperature is measured. This reference temperature will not be absolute zero degree Celsius. So Cold Junction Compensation is done inorder to avoid signal conditioning errors. The formulas are used to convert CJC voltage to temperature value. NIST standard sheet provides the coefficient values. The obtained temperature is checked for linearity and high amplification is done to get better results.

To determine the temperature at the thermocouple junction we can start with (2) shown below, where V_{MEAS} is the voltage measured by the data acquisition device, and V_{TC} ($T_{TC} - T_{ref}$) is the Seebeck voltage created by the difference between T_{TC} (the temperature at the thermocouple junction) and T_{ref} (the temperature at the reference junction)

$$V_{MEAS} = V_{TC} (T_{TC} – T_{ref}) \qquad (2)$$

NIST thermocouple reference tables are generated as shown in Table.1 with the reference junction held at 0 °C.

Table.1. NIST Standard table



	Range				
Voltage:	-8.095 to 0 mV	0 to 21.840 mV	21.840 to 45.494 mV	45.494 to 57.953 mV	57.953 to 69.
Temperature:	-210 to 0°C	0 to 400°C	400 to 800°C	800 to 1000°C	1000 to 12
	Coefficients				
T_0	-6.4936529E+01	2.5066947E+02	6.4950262E+02	9.2510550E+02	1.05112
V_0	-3.1169773E+00	1.3592329E+01	3.6040848E+01	5.3433832E+01	6.09560
p_1	2.2133797E+01	1.8014787E+01	1.6593395E+01	1.6243326E+01	1.71560
p_2	2.0476437E+00	-6.5218881E-02	7.3009590E-01	9.2793267E-01	-2.59310
p_3	-4.6867532E-01	-1.2179108E-02	2.4157343E-02	6.4644193E-03	-5.83398
p_4	-3.6673992E-02	2.0061707E-04	1.2787077E-03	2.0464414E-03	1.99541
q_1	1.1746348E-01	-3.9494552E-03	4.9172861E-02	5.2541788E-02	-1.53055
q_2	-2.0903413E-02	-7.3728206E-04	1.6813810E-03	1.3682959E-04	-2.95239
q_3	-2.1823704E-03	1.6679731E-05	7.6067922E-05	1.3454746E-04	1.13401

We can rewrite (2) as shown in (3) where V_{TC} (T_{TC}) is the voltage measured by the thermocouple assuming a reference junction temperature of 0 °C, and V_{TC} (T_{ref}) is the voltage that would be generated by the same thermocouple at the current reference temperature assuming a reference junction of 0 °C:

$$V_{MEAS} = V_{TC} (T_{TC}) – V_{TC} (T_{ref}) \qquad (3)$$

$$V_{TC} (T_{TC}) = V_{MEAS} + V_{TC} (T_{ref}) \qquad (4)$$

In (4), the computed voltage of the thermocouple assumes a reference junction of 0 ° C. Therefore, by measuring V_{MEAS} and T_{ref} , and knowing the voltage-to-temperature relationship of the thermocouple, we can determine the temperature at the primary junction of the thermocouple.

There are two techniques for implementing CJC when the reference junction is measured with a direct-reading sensor: hardware compensation and software compensation. A direct-reading sensor has an output that depends on the temperature of the measurement point. Semiconductor sensors, thermistors, or RTDs are commonly used to measure the reference-junction temperature. For example, several National Instruments thermocouple measurement devices include high-accuracy thermistors located near the screw terminals where thermocouple wires are connected.

With hardware compensation, a variable voltage source is inserted into the circuit to cancel the influence of the cold-junction temperature. The variable voltage source generates a compensation voltage according to the ambient temperature that allows the temperature to be computed assuming a constant value V_{TC} (T_{ref}) in Equations (3) and (4). With hardware compensation, we do not need to know the temperature at the data acquisition system terminals when computing the temperature of the thermocouple. This simplifies the scaling equation. The major disadvantage of hardware compensation is that each thermocouple type must have a separate compensation circuit that can add the correct compensation voltage. This disadvantage results in additional expense in the circuit. Hardware compensation is often less accurate than software compensation.

Alternatively, we can use software for CJC. After a direct-reading sensor measures the reference-junction temperature, software can add the appropriate voltage value to the measured voltage that compensates for the cold-junction temperature. Equation (3) states that the measured voltage, V_{MEAS}, is equal to the difference between the voltages at the hot junction (thermocouple) and cold junction.

Thermocouple output voltages are highly non-linear; the Seebeck coefficient can vary by a factor of three or more over the operating temperature range of some thermocouples. Therefore, we must either approximate the thermocouple voltage-versus-temperature curve using polynomials, or use a look-up table. The polynomials are in the following form where v is the thermocouple voltage in volts, T is the temperature in degrees Celsius, and a_0 through a_n are coefficients that are specific to each thermocouple type:

For voltage -to- temperature conversion (5),

$$T = a_0 + a_1 v + a_2 v^2 + ...+ a_n v^n \qquad (5)$$

The temperature -to- voltage conversion during cold junction temperature measurement is given by (6),

$$v = c_0 + c_1\ T + c_2\ T^2 + ...+ c_n\ T^n \qquad (6)$$

Initially the Cold Junction Temperature of the thermocouple is measured and it is converted into equivalent voltage. The reference temperature to CJC voltage conversion is given by the formula in (7,)

$$V = V_0 + \frac{(T - T_0)(p_1 + (T - T_0)(p_2 + (T - T_0)(p_3 + (T - T_0) p_4)))}{1 + (T - T_0)(q_1 + q_2 (T - T_0))} \qquad (7)$$

Where T_{cj} is the cold junction temperature, V_{cj} is the computed cold junction voltage, and the T_0, V_0, p_i and q_i are coefficients. And the coefficients are selected based on the thermocouple type using NIST Table.

To calculate the CJC voltage and CJC temperature. CJC voltage.vi is used as sub VI. Thermocouple type and CJC channel are given as controls. DAQmx driver has predefined VI's for creating channel, reading and clearing task. The sensor connected to the channel 0 of NI 9211[3] acquires input and it is read by DAQmx read. The value read from thermocouple is defined for CJC Temperature. This CJC temperature is converted into CJC Voltage for dynamic analysis.

The reference temperature acquired from ice bath is converted to Cold Junction Compensation(CJC) voltage. The array represents the t_0 , v_0 , p and q coefficients given as input to the math script node through index array. The thermocouples specified in the array are in the order. The thermocouple type and reference temperature T_{CJ} are also given as controls. The formula is entered in the MathScript Node and CJC Voltage is obtained as the output interms of millivolt. The error in and error out terminals are provided to bypass if any error occurs.

The Sub VI is developed to have Thermocouple channel as control signal and produces the Thermocouple Voltage as output. The measured voltage is added with CJC compensation voltage. The effective voltage is converted into the equivalent temperature. DAQmx is used for creating channel, sampling clock, starting task, reading values, stopping task and clearing VI. The For loop is used for reading 30 values continuously and finally displaying a single output value. The array elements from the For loop are added and divided with number of samples to produce final Thermocouple Voltage.

The obtained CJC mV is converted into thermocouple temperature. Here the control inputs are thermocouple types, CJC voltage, mV range and the temperature interms of ^{0}C is obtained as the output from MathScript Node. The array represents the T_0 , v_0 , p and q coefficients which are obtained from the NIST standard table.

The CJC voltage to temperature conversion formula is given by,

$$T = T_0 + \frac{(V - V_0)(p_1 + (V - V_0)(p_2 + (V - V_0)(p_3 + (V - V_0)p_4)))}{1 + (V - V_0)(q_1 + (V - V_0)(q_2 + (V - V_0)q_3))} \quad (8)$$

The CJC compensated voltage is given to the filter circuit to remove the noise signals and amplified with the gain of 31.25. The output voltage from thermocouple is in the range of -80mV to 80mV. Its offset shifted to 0-160mV and then amplified with the gain of 31.25 to reach the voltage range of 0-5V.

Amplified voltage = 31.25 x CJC compensated voltage

The ADS1240 ADC is used with the 24-bit resolution and delta-sigma configuration. The amplified input voltage is given to the ADC input. The 0-5 voltage converted into (0-2^{24} -1= 0 to 16777215 bits) using the below mentioned formula.

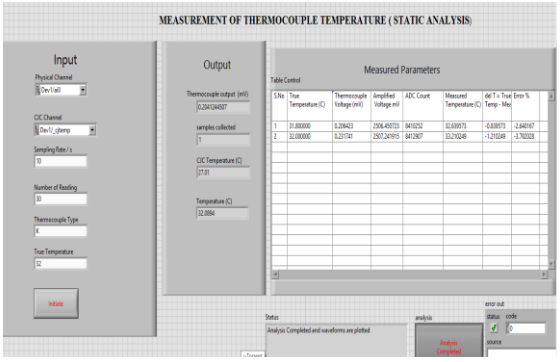
ADC Count = (Input voltage in mV / 5000) x 16777216 bits

Then mV to Temperature ADC count is coded. Thermocouple range.vi and mV to temperature.vi are used as sub vi’s. The controls are the Thermocouple range, CJC voltage, Thermocouple mV and error in status code. The indicators are CJC voltage, ADC count, Linearity range, Temperature, ADC Vin, Linearity region and Thermocouple measuring range. Linearity range is selected from the output mV of thermocouple range. The string array contains the thermocouple range for different types of thermocouple. Thermocouple measuring linearity region is determined by selecting the accurate range of thermocouple from the obtained mV.

The mV range for every type of thermocouple is selected and by using case structure, Inrange and coerce icon is used to check whether the thermocouple voltage range lies in the limit or not. The mV range varies for every type of thermocouple. Based on the upper and lower limit in the Inrange icon, the select terminal chooses the appropriate mV range for the given Thermocouple type and the voltage. The error checking block is present to indicate if the voltage value is out of range.

III. RESULTS AND DISCUSSION

Static analysis is done for a particular true temperature value. Variations in temperature can be obtained by running the vi again and again. Stable temperature applications which require slow changes can use static analysis. Linearity is the major parameter in Static analysis. The physical channel and CJC channel are selected based on the connection of thermocouple with the NI 9211 hardware. The sampling rate is given as 10 and the 30 readings are obtained for a single table input. The Thermocouple type and True temperature are given as inputs. After specifying all the inputs, the initiate is clicked. The Thermocouple mV obtained is amplified and ADC count is calculated. The error % is calculated by finding the difference between the True temperature and Measured temperature. The Static analysis of measurement of temperature of thermocouple is shown in Fig.2.



MEASUREMENT OF THERMOCOUPLE TEMPERATURE (STATIC ANALYSIS)

Input

Physical Channel: Dev1/ai0

CJC Channel: Dev1/_cjtemp

Sampling Rate / s: 10

Number of Reading: 30

Thermocouple Type: K

True Temperature: 32

Output

Thermocouple output (mV): 0.2041244507

samples collected: 1

CJC Temperature (C): 27.01

Temperature (C): 32.0894

Measured Parameters

Table Control

S.No	True Temperature (C)	Thermocouple Voltage (mV)	Amplified Voltage mV	ADC Count	Measured Temperature (C)	del T = True Temp - Mea	Error %
1	31.800000	0.206423	2506.450723	8410252	32.639573	-0.839573	-2.640167
2	32.000000	0.231741	2507.241915	8412907	33.210249	-1.210249	-3.782028

Status: Analysis Completed and waveforms are plotted

error out: status ✓ code 0

Fig.2. Front panel of Static analysis

The waveforms are plotted for True Temperature Vs Thermocouple Voltage, Amplified Voltage, ADC count and Measured Temperature as shown in Fig.3. The waveforms implies that the static analysis produces non-linear variation in temperature. Thus non-linearity is obtained as the result of Static analysis.

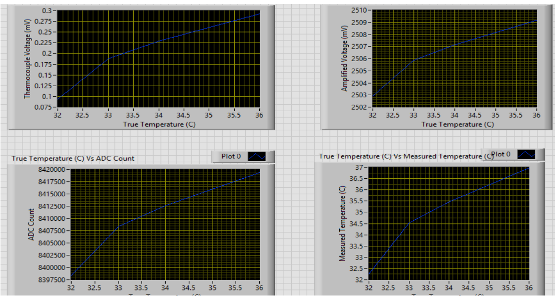
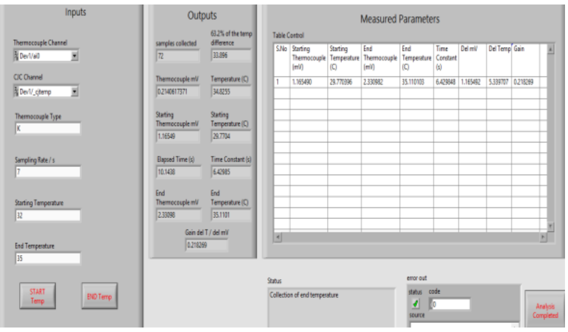


Fig.3. Waveforms of Static analysis

The Front panel of dynamic analysis shown in Fig.4. explains the temperature calculation for a range of temperature. The input parameters are initialized and Starting and Ending temperature is mentioned. The samples are collected and the process starts when the Start temperature is reached. The Time constant starts counting when the start temperature is obtained. The Time constant calculates the time taken by the thermocouple to reach 63.2% of the temperature difference between the starting and end temperature. Gain is calculated using the formula del T/ del mV.



Inputs

Thermocouple Channel: Dev1/ai0
CJC Channel: Dev1/_cjtemp
Thermocouple Type: K
Sampling Rate / s: 7
Starting Temperature: 32
End Temperature: 35

Outputs

samples collected: 72
63.2% of the temp difference: 33.896
Thermocouple mV: 0.2140617371
Temperature (C): 34.8255
Starting Thermocouple mV: 1.16549
Starting Temperature (C): 29.7704
Elapsed Time (s): 10.1438
Time Constant (s): 6.42985
End Thermocouple mV: 2.33098
End Temperature (C): 35.1101
Gain del T / del mV: 0.218269

Measured Parameters

Table Control

S.No	Starting Thermocouple (mV)	Starting Temperature (C)	End Thermocouple (mV)	End Temperature (C)	Time Constant (s)	Del mV	Del Temp	Gain
1	1.165490	29.770396	2.330982	35.110103	6.429848	1.165492	5.339707	0.218269

Status: Collection of end temperature

error out
status ✓ code 0
source

Fig.4. Front panel of Dynamic analysis

The waveforms for dynamic analysis is shown in Fig.5. The Time Vs Measured temperature, Measured Thermocouple Voltage are plotted. The gain is increased in dynamic analysis.

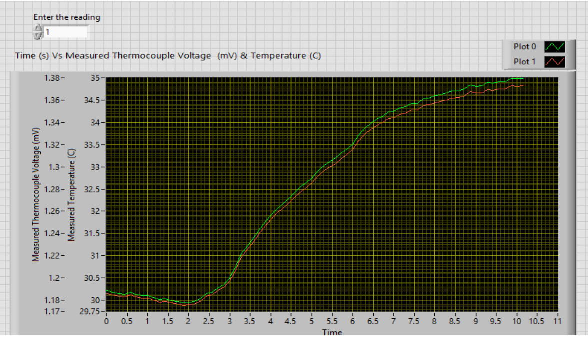


Fig.5. Waveforms of Dynamic analysis

IV. CONCLUSION

The measurement of temperature using the thermocouple included the signal conditioning stages of reference temperature sensor (for Cold Junction Compensation), high amplification and linearization. The Thermocouple voltage(mV) is converted into temperature(^{0} c) which can be used in real time applications to have fast data acquisition rate. The errors in the amplification, ADC count and linearization are identified and compensated. In Static analysis, non-linearity is obtained for variation in temperature. In Dynamic analysis, gain is increased Comparision and evaluation of performance of software and hardware based signal conditioning will be done and implemented in FPGA in the future.

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