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Temperature Measuring with Thermocouple and USB Data Acquisition Module

Nicolae Pătrăşcoiu, Adrian Marius Tomuş

University of Petroşani, Universității 20, 332014 Petroşani, ROMÂNIA
e-mail: patrascoiu@upet.ro, adi_tomus@yahoo.com

Abstract

Thermocouples are the most popular temperature sensors. They are cheap, interchangeable, have standard connectors and can measure a wide range of temperatures. The main limitation is accuracy, system errors of less than 1°C can be difficult to achieve with usual system measurement. Using a data acquisition system it can be possible to reduce measurement system errors. We propose a temperature system measurement and virtual instrument based on National Instruments USB 6008 data acquisition module.

Key words: *thermocouple, data acquisition, USB-6008, virtual instrument.*

Thermocouple

Thermocouple is temperature sensor suitable for use with any make of instrument designed or programmed for use with the same type of thermocouple. Thermocouple is based on the principle that when two dissimilar metals are joined a predictable voltage will be generated that relates to the difference in temperature between the measuring junction and the reference junction. It is important to appreciate that thermocouple measure the temperature difference between two points, not absolute temperature [9]

Starting from this observation is obvious that to measure the relative temperature T_x is needed to establish a reference and this is the temperature corresponding freezing point ("ice-point" temperature) of water, T_{ice}. That means a new junction is added and held in an ice bath at T_{ice} (0°C/32°F). The thermocouple circuit shown in figure 1 represents the basis upon which thermocouple standard tables have been established. The standards community together with modern metallurgy has developed special material pairs specifically for use as thermocouples [3].

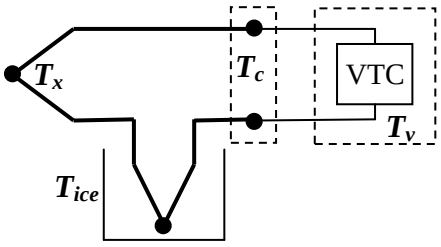

Fig.1. Thermocouple Topology.

Table 1 displays industries eight popular standard thermocouples and their typical attributes. Manufacturers may fabricate thermocouples of a given type with variations in composition; however, the resultant temperature versus voltage relationships must conform to the thermoelectric voltage standards associated with the particular thermocouple type.

Table 1. Industries standard thermocouples

TYPE	MATERIALS	TYPICAL RANGE [^{O}C]
T [1,2]	Copper (Cu) vs Constantan	-270 to 400
J [1,3]	Iron (Fe) vs Constantan	-210 to 1200
K	Chromel vs Alumel	-270 to 1370
E	Chromel vs Constantan	-270 to 1000
S	(Pt-10%Rh) vs Pt	-50 to 1768
B	(Pt-13% Rh) vs (Pt-6% Rh)	0 to 1820
R	(Pt-13%Rh) vs Pt	-50 to 1768
N	(Ni-Cr-Si) vs (Ni-Si-Mg)	-270 to 1300

Standard mathematical power series models have been developed for each type of thermocouple. These power series models use unique sets of coefficients which are different for different temperature segments within a given thermocouple type. Unless otherwise indicated, all standard thermocouple models and tables are referenced to zero degrees Centigrade, 0°C.

Equation (1) illustrates the power series model used for all thermocouples except K type, which is illustrated by equation (2) where the exponential term is added to account for special effects.

$$VTC = \sum_{i=0}^{n}\left(C_i \cdot (T_x)^i\right), \quad [mV], \tag{1}$$

$$VTC = \sum_{i=0}^{n}\left(C_i \cdot (T_x)^i\right) + A_0 \cdot e^{A_1 \cdot (T_x - A_2)^2}, \quad [mV]. \tag{2}$$

These equations together with the coefficients C_i and A_i have been adopted as standards by the American Society for Testing and Materials (ASTM) and the International Electrotechnical Commission (IEC).

These equations with their different sets of coefficients are difficult to use in directly determining actual temperatures when only a measured thermocouple voltage [VTC] is known. Therefore, inverse models have been developed to determine temperatures from measured thermocouple voltages. Equation 3 represents this inverse model.

$$T_x = \sum_{i=0}^{n}\left(D_i \cdot (VTC)^i\right), \quad [^{o}C], \tag{3}$$

where VTC is in milivolts.

Modern signal conditioning modules use semiconductor electronics, which eliminate clumsy ice-baths by electronically simulating reference junction “ice-point” temperatures. This process is referred to as Cold-Junction-Compensation, CJC. In addition, these modern signal-conditioning modules linearize the non-linear behavior of Seebeck coefficients and provide linear scaled outputs in volts or amperes per degree.

Temperature Acquisition System

Because different thermocouple types have different voltage characteristics that means different output voltage to the same temperatures is necessary to select the proper characteristics to the proper thermocouple type when a replacement thermocouple is required. As well to prevent large errors that can be developed is necessary to select the proper thermocouple extension wire according to the proper thermocouple wire; usually the copper extension wires are used [9].

This acquisition system is based on using the module NI USB-6008 that is controlled by an application developed in LabVIEW and called virtual instrument.

The NI USB-6008 provides connection to 8 analog input (AI) single-ended or 4 differential, software selectable channels, 2 analog output (AO) channels, 12 digital input/output (DIO) channels, and a 32-bit counter with a full-speed USB interface. For this application we use two differential analog inputs that range can be chosen between ± 10 V ... ± 1 V and is chosen the input range ± 2.5 V [7].

One of the inputs (AI0) is used to retrieve the signal from the sensor and the other input (AI1) is used to retrieve the signal from a thermistor used for cold junction (CJC) temperature compensation.

Considering the field of measurement 0 ... 200 ^{o}C the maximum voltage generated is obtained for the K thermocouple and for the limit about 200 ^{o}C the voltage is only 20.872 mV. In these conditions to use the entire dynamic range of the converter that is -2.5 ... 2.5 V is necessary to use an amplifier with a gain of 120. To achieve this gain is used an instrumentation amplifier, figure 2, such as the INA114 which gain G is given by the relation [2], [6]:

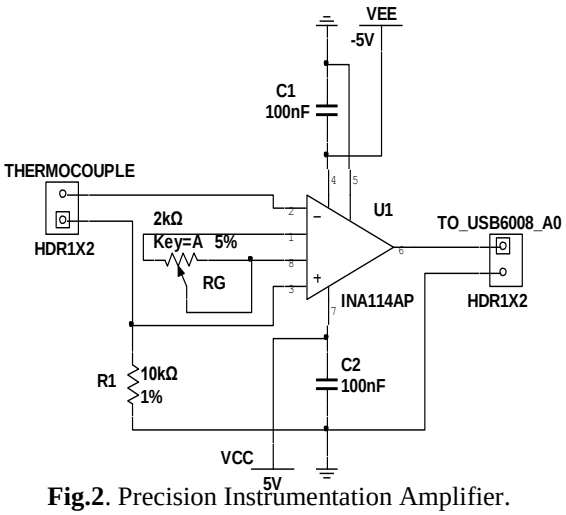

Fig.2. Precision Instrumentation Amplifier.

$$G = 1 + \frac{50k\Omega}{R_G} \qquad (4)$$

yields a value of required resistance R_G by about 1 kΩ and is choose a variable resistance with value of 1 kΩ so that is offered a possibility of carrying out an adjustment of the gain. Measured thermocouple voltage (VTC) adapted to cover the dynamic range of the analog-digital converter becomes input voltage U_{A0}

To achieve the compensation of cold junction temperature is used a thermistor with negative temperature coefficient (NTC) that has the following parameters: R_T=10 kΩ nominal resistance @ 25 ^{o}C, Steinhart-Hart equation parameters: A = 0.001129148; B = 0.000234125; C = 8.76741E-8.

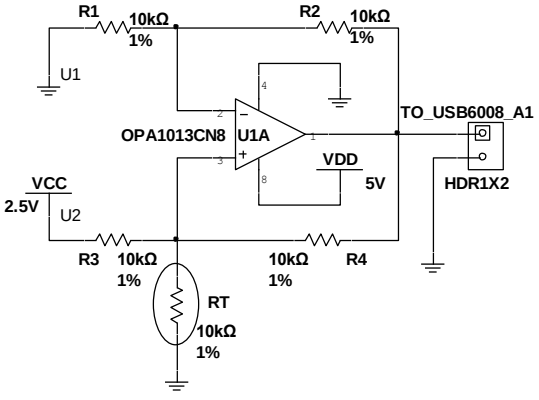

Fig.3. Thermistor used to CJC compensation.

Thermistors have some functional characteristics such as good sensitivity, small size and low cost price and these features recommend thermistors for use as elements of cold junction compensation temperature. But must take into account the fact that they have a strong nonlinearity R-T characteristic which can be described by the Steinhart-Hart equation:

$$T = \left[A + B \cdot (\ln R_T) + C \cdot (\ln R_T)^3\right]^{-1}, \quad (5)$$

where T is the absolute temperature (in Kelvin) and A, B, and C are constants whose values depend on the constructive parameters of the thermistor and which for this application have been presented above [3], [4].

As the NI USB-6008 module analog input measures only voltage, we will need to provide a current source to convert the resistance to voltage. For this is used Howland mounting (figure 3)

like a constant current source. The amount of current through thermistor does not depend on the resistance R_T and it is given by the relations [3], [4]:

$$I_T = \frac{1}{R_4} \cdot \left(\frac{R_4}{R_3} \cdot U_2 - \frac{R_2}{R_1} \cdot U_1 \right) = \frac{1}{R_3} \cdot U_2 \,. \tag{6}$$

Applied tension to the analog input AI1, U_{A1} is proportional to the amount thermistor resistance, as the relation:

$$U_{A1} = \frac{R_T}{R_3} \cdot (U_2 - U_1) \cdot \left(1 + \frac{R_1}{R_2} \right) - \frac{R_2}{R_1} \cdot U_1 = R_T \cdot \frac{1}{R_3} \cdot \left(1 + \frac{R_1}{R_2} \right) \cdot U_2 = R_T \cdot \frac{2}{R} \cdot U_2 \tag{7}$$

Wherefrom

$$R_T = \frac{R}{2 \cdot U_2} \cdot U_{A1} \tag{8}$$

The two tensions U_{A0} and U_{A1} are applied to the data acquisition module NI USB-6008 at the analog inputs AI0 respectively AI1.

Virtual Instrument

Virtual instrument (VI), which is the acquisition process administration, has two major components: the diagram bloc that represents the properly program and the front panel that represents the user interface [1].

The main programming structure from the diagram bloc of virtual instrument for this application, shown in figure 4 is a While Loop and acquisition process is performing by using DAQmx functions [5].

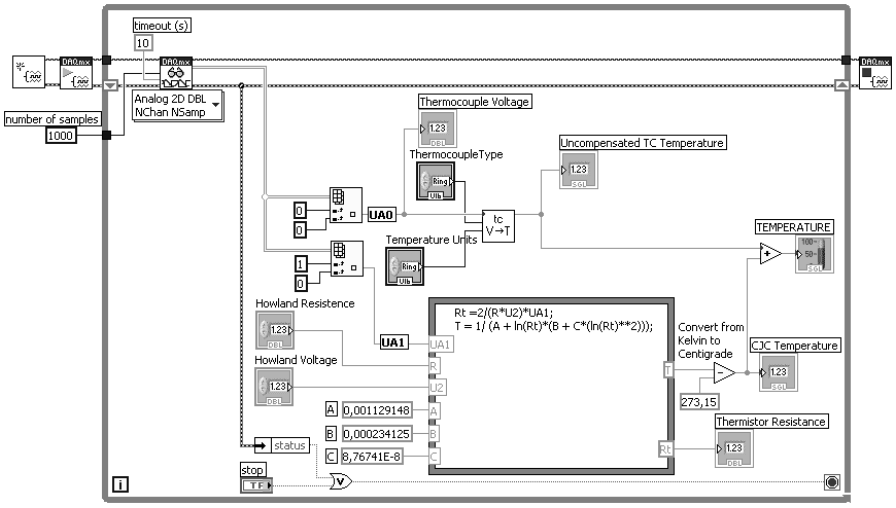

Fig.4. Diagram bloc of the virtual instrument.

The first function used is the NI-DAQmx Create Virtual Channel which creates a virtual channel and adds it to a task. In this application the NI-DAQmx Create Virtual Channel function creates two analog input channels. The second function used is the DAQmx Start Task. This function explicitly transitions a task to the running state. In this application, in the running state, the function starts the task which performs the specified acquisition. The third function used is

the DAQmx Read and this function reads samples from the specify task or virtual channels [8]. In this application, the function reads analog inputs AI0 and AI1.

The value of voltage U_{A0} taken by the analog input AI0 is displayed as **Thermocouple Voltage** and is used to determine temperature of the thermocouple. To determine the thermocouple temperature is used relationship (3) customized for different thermocouples and specific areas of their temperatures. To achieve voltage-temperature conversion is used a SubVI (V→T) that has like base element a Case structure. Value wired to the Case selector terminal that select which case is executed at a time is generated by the user via front panel control **Thermocouple type**. The selection of areas of measurement for each thermocouple is done by comparing the values of these areas limits, taken from the static characteristic to the corresponding generated voltage. Practically, in this way, it generated a number of cases equal to the number of subdomains and these cases are properly selected.

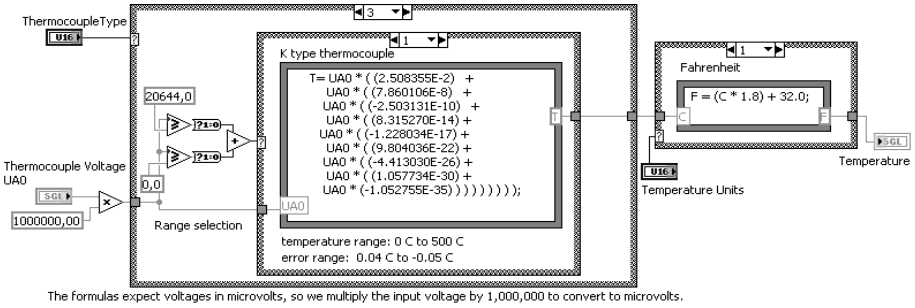

Fig.5. SubVI Voltage to Temperature (V →T).

The relationship between the temperature difference and the output voltage of a thermocouple is nonlinear and is given by a complex polynomial equation. As mentioned above, to use relationship (3) is necessary to choose values of D_i coefficients in agreement with ITS90 standard. To achieve this requirement is used subVI (V→T), shown in figure 5, whose block diagram is exemplified for a thermocouple type K used for the temperature range 0 ... 500 ° C. For type K thermocouple field measurement is -200 ... 1375 ^{o}C, and this area is divided into 3 subdomains such -200 ... 0 °C, 0 ... 500 °C, respectively 500 … 1375 °C, each subdomain is characterized by different coefficients for the static characteristic defined by relationship (3). The selection of each of the three cases is based on the values of tension U_{A0} generated for 0 ^{o}C and 500 ^{o}C ie 0 and respectively 20644 μV [1].

Virtual instrument ensure also the selection of units for measuring temperature via control **Temperature Units** on the front panel by selecting the corresponding relations for conversion.

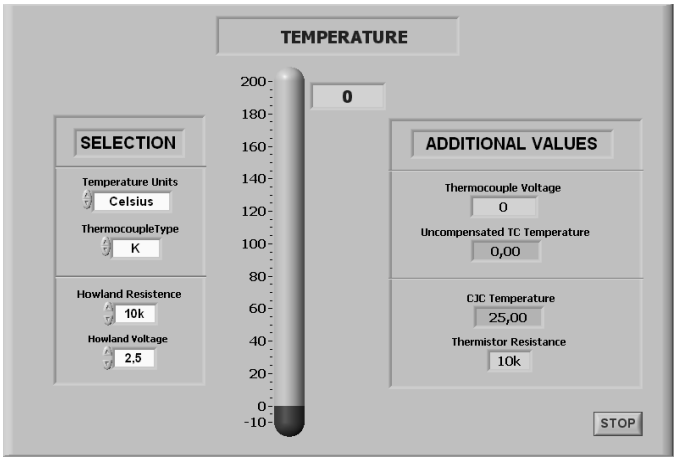

Fig.6. Front Panel of the Virtual Instrument.

The front panel is the user interface of the virtual instrument and it is built with controls and indicators, which are the interactive input and output terminals of the virtual instrument. The front panel for this application, figure 6, contains controls mentioned above, plus controls for setting parameters of the Howland mounting i.e. **Howland Resistance** and **Howland Voltage** [5]. Indicators on the front panel are used to display the measured

temperature (**Temperature**) and also to display additional values such as voltage generated by thermocouple (**Thermocouple Voltage**), the uncompensated temperature (**Uncompensated TC Temperature**), reference junction temperature (**CJC Temperature**) and the thermistor resistance value (**Thermistor Resistance**)

Conclusions

Using the data acquisition system and virtual instrument enables a severe reduction of measuring errors. This reduction is possible by choosing appropriate static characteristic of thermocouple depending of type of thermocouple, domains and subdomains of the temperature which is measured at a time.

Changes into measurement scheme such as thermocouple or thermistor replacement may be further made because the user has the possibility to select through the controls on the front panel thermocouple and thermistor type used at a time and temperature of their use.

It is also possible the simultaneous use of several types of thermocouples virtual instrument offering accuracy better than 0.1% for measuring the temperature with any of them.

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Măsurarea temperaturii folosind termocupluri conectate la sisteme USB de achiziţie a datelor

Rezumat

Termocuplurile sunt printre cei mai utilizaţi senzori de temperatură. Acestea sunt ieftine, interschimbabile, au conectori standard şi pot fi utilizate pentru o gamă largă de temperaturi. Principala limitare este dată de precizie, astfel măsurări cu erori mai mici de 1 °C nu pot fi realizate cu sistem de uzuale măsurare. O posibilitate de reducerea erorilor de măsurare o reprezintă utilizarea unui sistem de achiziţii şi prelucrare a datelor prin facilitatea oferită de alegere a caracteristicii corespunzătoare a termocuplului. În această lucrare propunem un sistem de măsurare a temperaturii bazat pe de modulul de achiziţie de date USB 6008 produs de National Instruments precum şi un instrument virtual pentru controlul măsurării şi prelucrare a datelor.