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Laboratories practices in engineering educational courses: the problem of thermocouple cold junction compensation with calibration error correction

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Abstract- In this paper the preliminary work of laboratory practices developed for didactic purposes for undergraduate courses at the Engineering Faculty of Polytechnic of Bari is presented.
The educational purposes of these experiments can be summarized as follow:

- to grant students the opportunity to verify theoretical arguments introduced in theoretical lessons;
- to give technical skills;
- to integrate research work and educational programs promoting the insertion of student in the scientific community.

In this paper a technical solution useful to measure temperature by means of thermocouples is described; the main goal of the proposed technique is that it employs only one programmable multimeter and devices commonly available in university laboratories.

I. Introduction

When two dissimilar conductors, such as metals, alloys or non-metals, are welded at both ends to form a loop and the two junctions are at different temperatures, in this loop will flow a current. This circuit is known as *thermocouple*. Thermocouples (TCs) are commonly used in industrial field and in test and research laboratories for measuring temperature.
When one junction is cut, at the free ends a small open-circuit voltage can be measured.
The Seebeck e.m.f. is a function of the temperature gradient between the junction and the open terminals is given by:

$$V = (S_B - S_A)\cdot(T_{hot} - T_{cold}) = S_{AB}\cdot\Delta T \tag{1}$$

where S_{AB} is the Seebeck coefficient and ΔT is the temperature gradient between junctions.
The point of conductors' connection is called hot junction or *measuring junction* and the free end points are named cold junction (CJ) or *reference junction.* [1], [2]
TCs make differential temperature measurements, so we have to measure the reference junction temperature to have right results, or we have to keep the reference junction at a known and constant temperature.
Traditionally, thermocouples were used with a cold junction immersed into a reference ice bath to maintain its temperature at 0 °C.
In many applications it may be difficult to have an ice bath available, so we have to measure the CJ temperature to obtain a correction in sensing voltage by means of some other temperature transducer in order to adjust it [3].
If the signal from the cold junction sensor is used directly by a circuit we have a *hardware CJ compensation* elsewhere, if the signal is digitized and elaborated by some software we have a *software CJ compensation* [4]; the first technique requires a specialized and often costly hardware specifically designed for the particular type of TC in use, the second requires some digitizing hardware and a computational core but can be easily adapted to all types of thermocouples.
In this paper the authors describe a technique that permits the cold junction compensation (CJC) by means of integrated temperature transducers. The adopted CJ temperature measurement method permits to use only a programmable DMM to measure both the thermocouple voltage and the output of the CJ temperature sensor.

II. Basic thermocouple theory

Unfortunately Equation (1) is not linear because the Seebeck coefficients S_{AB} between two materials A and B depend on temperature; for this reason, the voltage-to-temperature relationship is commonly approximated using Taylor polynomials expansion. If $T_{cold} = 0°C$, the open circuit TC voltage is given by:

$$v = \sum_{n=0}^{N} c_n \cdot T_{hot}{}^n \tag{2}$$

where N $\in$[6, 10], T is the temperature in degree Celsius, v is the thermoelectric voltage in µV and c_n are coefficients for temperature-to-voltage conversion; for K–type thermocouples there is an additional term to take into account in the equation, so the (2) is expanded as:

$$v = c_0 + c_1 T_{hot} + c_2 T_{hot}{}^2 + c_3 T_{hot}{}^3 + ... + c_{94} T_{hot}{}^9 + 118.5976 e^{(-1{,}183432E-4)(T_{hot} - 196.9686)^2}$$

Generally, for both kinds of compensation we measure the CJ temperature, then calculate the voltage correction using the inverse formula of (2):

$$T_{hot} = \sum_{n=0}^{N} a_n \cdot v^n \tag{3}$$

This function is the transfer relation between thermocouple temperature and its open circuit voltage when $T_{cold} = 0°C$; a_n are coefficients specific for each thermocouple type. The direct and inverse coefficients are reported by NIST for each type of TC [5].

This voltage is summed to sensed voltage

$$V_x = V_{Meas} + V_{cold} \tag{4}$$

and the result is used to calculate the effective measure junction voltage.

Then, using (3), we can determine the temperature of thermocouple.

III. Error calibration and compensation technique

In many applications the software compensation involves the use of semiconductor sensors, for example LM35CZ, thermally coupled to the cold junction.

Since LM35xx temperature transducer has a voltage output, we should use a multiple input DAQ device or two DMMs or one DMM and a switch matrix to acquire these signals at same time.

Alternatively, if we want to continue to use only one DMM, we can use a semiconductor sensor with a current output proportional to the absolute temperature.

In this paper we describe a technique to measure the temperature using a K – type TC (K-type from nickel-chromium and nickel-aluminium) [6], an Agilent 34401A Programmable Digital Multimeter, an Agilent E3631A Triple Output DC Power Supply (PWS), and an Analog Devices' AD590KH 2 terminal current output IC temperature transducer.

In AD590 measurements the calibration error is the primary contributor to the total error; from its specifications it can be seen that at 25°C the maximum calibration error is ±2.5°C. The AD590 data sheet suggests the use of a variable resistor to adjust this error, but in this way we have a current-to-voltage conversion.

The proposal of the authors is to use a current mirror configuration to keep the current output but also introducing the ability to trim the output value.

The used current mirror is a traditional Widlar current mirror in which emitter degeneration resistors are inserted on both transistors in order to obtain a current ratio calibration.

The current mirror is made using an LM3046 integrated transistor array; Figure 1 shows the schematic diagram of the developed circuit (numbers on transistor terminals indicate the corresponding pin on LM3046). The LM78L05 is used to reduce the systematic error due to the supply voltage.

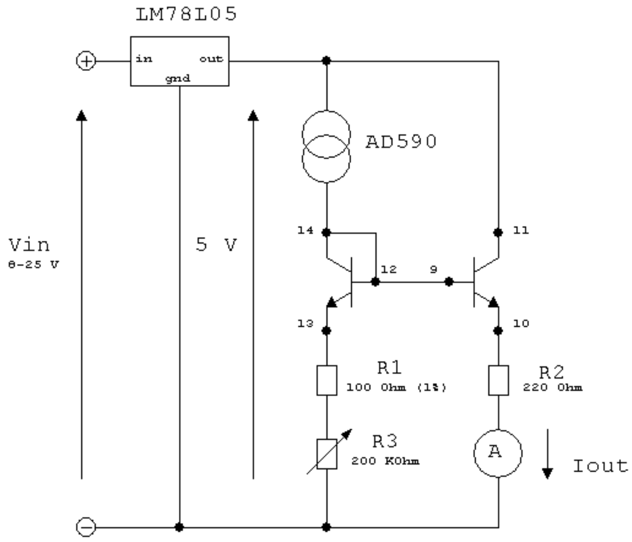


Figure 1. AD590 - current mirror circuit scheme

IV. Experiment description and results

The first problem pertains to the calibration of the circuit in Figure 1. In this step a LM35CZ precision temperature transducer is used. The LM35 [7] series are precision integrated-circuit temperature sensors, whose output voltage is linearly proportional to the Celsius temperature and is more accurate than AD590 series [8]. These sensors are powered by means of PWS; to make the calibration the LM35 is connected to the voltage input and the AD590 is connected to the current input of the same DMM as shown in Figure 2.

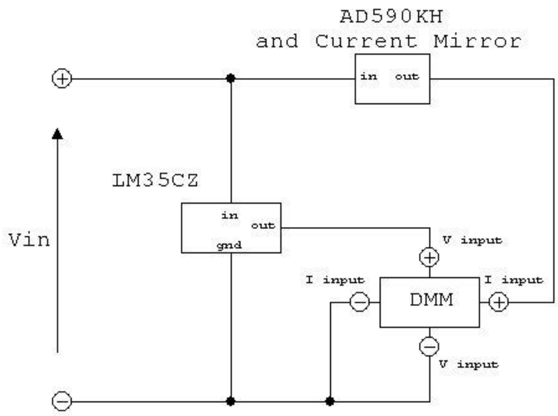


Figure 2. Block diagram of the calibration circuit

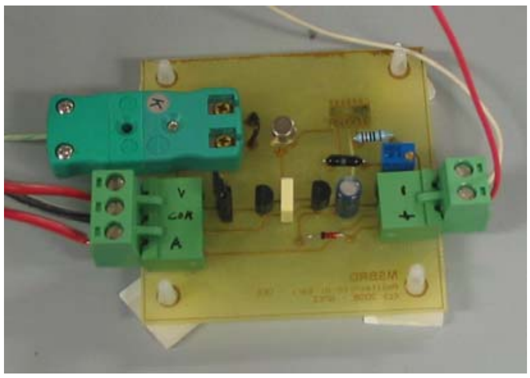
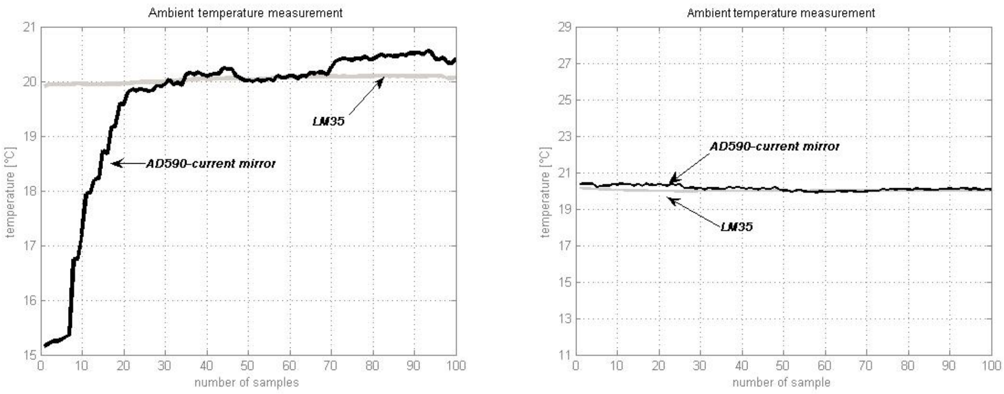


Figure 3. The realized calibration circuit

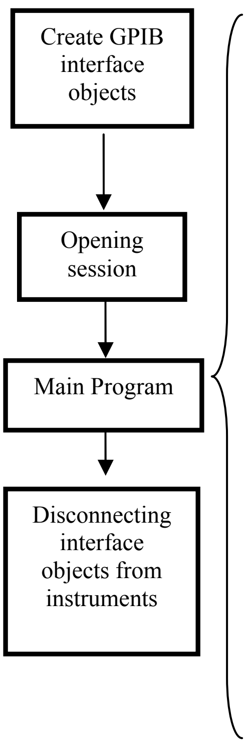
To calibrate the AD590-current mirror the variable resistor R3 is trimmed.
In Figures 4a and 4b the calibration error correction process is shown.



a) b)

Figure 4. a) Calibration error correction. b) Temperature after AD590 calibration

Whole process in supervised by Matlab® Instrument Control Toolbox™ (ICT); this toolbox is useful to communicate with instruments via communication protocols such as GPIB (IEEE 488), VISA, TCP/IP. In our experiment we have used the programmable instruments with GPIB interface.
In the following figure is shown the measurement loop.




```
fprintf(PWS,'output on')

%% Main program - Calibration error correction

for i=1:N
    command=sprintf('apply P25V, %f, %f',V_supply_range, I_supply);
    fprintf(PWS,command);
    V_LM(i) = query(DiM,'measure:volt:dc?','%s','%f'); %measured
voltage
    I_AD(i) = query(DiM,'measure:current:dc?','%s','%f');%measured
current

    T_LM(i) = V_LM(i)*100; % voltage - temperature conversion
    T_AD(i) = I_AD(i)*1e6 - 273.15; % current - temperature
conversion

% PLOT
    figure(1)
    plot(T_LM)
    hold on
    plot(T_AD,'r')
     title('Ambient temperature measurement')

    grid
    drawnow
    ylabel('temperature [°C]'), xlabel(number of sample')
    pause(1)

end

fprintf(PWS,'output off')
```

Figure 5. Block diagram and main code block of matlab script

Completed the calibration process it is possible to make the measurements of temperature by the thermocouple.
Above are reported few lines of the Matlab script that permit us to calculate the reference voltage in order to obtain the CJ software compensation.

```
Vref = C(1)+C(2).*T_F+C(3).*T_F.^2+C(4).*T_F.^3 ...
    +C(5).*T_F.^4+C(6).*T_F.^5+C(7).*T_F.^6 ...
    +C(8).*T_F.^7+C(9).*T_F.^8+C(10)*T_F.^9 ...
     + 118.5976*exp((-1.183432e-4).*(T_F-126.9686).^2);
V_H = V_H.*1e6; % measuring (hot) junction voltage
Vx = V_H+Vref;
Tx = A(1)+A(2).*Vx+A(3).*Vx.^2+A(4).*Vx.^3+A(5).*Vx.^4 ...
    +A(6).*Vx.^5+A(7).*Vx.^6+A(8).*Vx.^7+A(9).*Vx.^8+A(10).*Vx.^9;
```

V. Conclusion

The research of the best way to assure a high learning of theoretical concepts and the acquisition of good technical skills, is the main issue of university teaching team; in the authors' opinion laboratory practices are very important.
One of main important problem regarding the temperature measurement by means of thermocouple is the cold junction compensation. To this aim in many industrial applications, supervised by Automatic Test Equipment (ATE) systems, are used integrated sensor or the more expensive thermo-resistance. A possible compromise in cheapness and accuracy in measurement is the LM35 sensors series, but is necessary using two or more devices because both thermocouple and LM35 have voltage output.
In this paper the authors present a technique based on use of a current-output integrated sensor. The proposed conditioning circuit permit us to correct the calibration error and the use of only one DMM to measure both thermocouple voltage and sensor current improving measurement stability and accuracy.
Using Matlab® script and GPIB interface is possible to implement the transducers characteristic to easily solve the CJ compensation problem.
This technique is also used for educational use in laboratory practices as practical exercise including more aspects in the sensor use. In this way is possible to verify the theoretical arguments introduced into theoretical lessons.

References

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