

# UNCERTAINTY QUANTIFICATION USING THERMOCOUPLE AND ARDUINO® COMPATIBLE HARDWARE

L. R. R. da Silva,  
and J. R. Ferreira-Oliveira

Federal University of Uberlandia, School of  
Mechanical Engineering, Av. João Naves de  
Ávila, 2121, Bloco 1M, 38400-902,  
Uberlândia, MG, Brazil.  
leorrs@ufu.br  
jose.ricardo@ufu.br

## ABSTRACT

Temperature is a critical aspect in the control of processes in engineering. The measurement, however, must take into account not only the accuracy of the sensor but also the implementation costs and uncertainty. Thermocouples are one of the most widely used temperature measurement methods combining low costs, high measurement ranges, and relatively good accuracy. The acquisition system, however, is usually expensive. This paper evaluated the uncertainty in the temperature measurements of a K-type thermocouple using low cost Arduino® compatible hardware as a data acquisition system. This set was calibrated using a thermostatic distilled water bath at both freezing and boiling phase change points. The equations for uncertainty calculation were fully developed, and the procedures described serve as a reference for uncertainty assessment for thermocouples with other data acquisition systems. Although the calibration was the most significant contributor, the low variability of measurements shows the system has good stability and is a fine choice for industrial applications. The calculations are easy to implement as a routine for several measurements and guarantee results up to the international reference standard.

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## INTRODUCTION

Temperature measurement systems are widely used in industrial processes and research, with several different technologies available nowadays. Each has a determined operational principle, accuracy, and precision, which strongly influences sensor and equipment costs. High-temperature accuracy is necessary when performing material characterization and process monitoring of very delicate applications or dealing with inverse problems in heat and mass transfer. However, certain industrial cases in which small temperature oscillations do not disturb the process and final product dispense sensitive sensors' need. However, even in these scenarios, minimum quality and reliability should be guaranteed.

Even in the most precise temperature instruments, readings may vary due to systematic and random errors. Although the first should be measured and corrected, many sources of errors are difficult to determine or eliminate, such as those due to electromagnetic fields around electronic instruments or vibrations, among others. Therefore, according to metrology principles, a measurement cannot give the exact value of a measurand but only estimate it within

a specific range of quantified uncertainty given a determined confidence level (Vuolo, 1996).

The Guide for Expression of Uncertainty in Measurement-GUM (INMETRO, JCGM, 2008) provides a robust method for assessing uncertainty considering the different possible sources of errors during measurement. This procedure is essential for various reasons. First, if the output results do not come accompanied by a study of its reliability, this result cannot be trusted once there is no definition of how precise it was. Second, it is possible to determine the uncertainty associated with each possible source of error during the procedure, allowing operators to make any necessary adjustments to the measuring method or system. Finally, the expression of uncertainty guarantees traceability of all measures carried in different precision levels up to the international reference standard. The International Bureau of Weights and Measures defines through the SI the reference for each property to be measured (INMETRO, BIPM, 2012). During the 10th General Conference on Weights and Measures-CGPM in 1954, the official temperature unit would be the Kelvin. Besides, the triple point of water would serve as a fixed reference for 273.15 K. The International

Committee on Weights and Measures also accepted the Celsius as an official unit in 1990, meaning that 1 °C is equal to 1 K, which is the fraction of 1/273.15 of the temperature for the triple point of water.

According to Ross-Pinnock and Maropoulos (2016), thermocouples are the most used invasive sensors due to their low cost, wide measurement range, and accuracies up to 0.1 K. resistance-based temperature sensors (IPRT) also are used since they are more resistant to shock, vibration and contamination than thermocouples and bear accuracies up to 0.01 K. However, as a downside they are usually much more expensive, with platinum PT-100 being the most typical representative. Despite having accuracies up to 30 mK, negative temperature coefficient thermistors (NTCs) are not used as thermocouples because of their non-linear temperature-resistance curves. The most well-known method of non-invasive temperature measurement is IR radiation thermometry, which measures surface temperature concerning its emissivity. The main disadvantages of IR thermometry are the relatively low accuracy (about 1 K), high costs, and sensitivity to the surface condition.

For this reason, thermocouples are preferred in applications that require low-cost sensors. This work investigated the uncertainty of temperature measurements using a type K thermocouple with Arduino® compatible hardware and microcontroller as a data acquisition system. This combination yields low costs and a high potential for process automation. The detailed procedures and equations provide a methodology for assessing temperature uncertainty with thermocouples, even for different acquisition systems. The system was stable in all measurements with standard deviations less than 1 °C and expanded uncertainties less than 3 °C. The stability was worse in low temperatures but was still well within the maximum variation stated by the manufacturer. Finally, the method presented guarantees traceability of temperature results to the international reference standards, a good practice recommended by the GUM (INMETRO, JCGM, 2008) for all industrial and laboratory applications.

## UNCERTAINTY ASSESSMENT

Thermocouples work according to the Seebeck effect, in which an electric potential difference (DDP) appears in a circuit formed by two different materials if their two junctions are subjected to different temperatures. This way, if one of the junctions is kept at a known constant temperature, regarded as the cold junction, the temperature of the other regarded hot junction may be estimated by correlating it with the analogic voltage signal of the circuit (Ripple and Garrity, 2006). The latter can be measured by a voltmeter or converted to digital data. The cold junction temperature is measured by a second

temperature sensor, which is usually an NTC or IPRT. Both thermocouple and cold junction sensors should be calibrated to correct systematic errors and characterize their precision through uncertainty assessment.

Sârbu and Beniugă (2018) performed calibration and uncertainty measurements of type K thermocouples considering a reference type S thermocouple already calibrated. In his work, DDP was directly measured via a calibrated multimeter so that the measurement uncertainty calculated would relate only to sensor-related issues such as material inhomogeneity and nonlinearities. Nevertheless, this procedure would not be applicable for systems that already convert the voltage signals of cold junction probe and thermocouple to digital data and calculate the corresponding temperature according to thermocouple type. In such cases, the measured uncertainty will also account for errors about the whole system, such as possible measuring errors of the inbuilt voltmeter, or during analogic to digital conversion, and even the sensitivity to electromagnetic fields on how internal components were manufactured. The term related to cold junction sensors should also be considered separately. These terms were described by Manso (2013), whose values for each uncertainty parcel were defined arbitrarily or according to catalogs. In addition, a further correction might be necessary after thermocouple calibration because the temperature is determined after multiplying the DDP by the constant of the two materials of the circuit. For type K, this value is about 41.276  $\mu\text{V}/^\circ\text{C}$  (Maxim Integrated, 2015), but it might vary due to slight changes in wire chemical composition or manufacturing method.

Oliveira et al. (2020) studied uncertainty measurements with thermocouples to compare the obtained errors between an experiment and an analytic solution for unidimensional heat conduction. They expressed temperature uncertainty as in Eq. (1). An Agilent 34970 board was employed for data acquisition, which is a very precise system, and all measurements were performed in a temperature-controlled environment. That is not always the case for many industrial applications, and therefore the uncertainty related to cold junction compensation should also be expressed, as in Eq. (2), where  $\Delta T$  is the combined uncertainty,  $\overline{\Delta T}$  is the uncertainty due to variability around mean,  $\Delta R$  is the uncertainty due to finite resolution of the system,  $\Delta \text{ICJF}$  is the uncertainty due to cold junction compensation, and  $\Delta \text{IC}$  is the uncertainty due to the thermocouple, and system calibration. Considering the GUM methodology, Eq. (3) describes a general mathematical model for calculating the uncertainty of a measurement, where  $Y$  is the output and  $X_1, X_2, \dots, X_N$  are the input variables.

$$\Delta T = \overline{\Delta T} + \Delta R + \Delta \text{IC} \quad (1)$$

$$\Delta T = \overline{\Delta T} + \Delta R + \Delta \text{ICJF} + \Delta \text{IC} \quad (2)$$

$$Y = f(X_1, X_2, \dots, X_N) \quad (3)$$

As long as there are no correlations between the uncertainty sources, the combined standard uncertainty  $u_c(y)$  can be calculated through the law of uncertainty propagation shown in Eq. (4), where  $u(x_i)$  is the variance of each input variable  $X_i$  and the result of the partial derivative for each variable is called the sensitivity coefficient  $c_{x_i}$ . The variance is calculated for each variable depending on its evaluation type, which can be A or B, and the percentage contribution of the  $i$ -th variable results from the division of the product of squares in Eq. (4) by the combined standard uncertainty. A detailed explanation can be found in the Gum (Inmetro, Jcgm, 2008).

$$u_c^2(y) = \sum_{i=1}^N \left( \frac{\partial f}{\partial x_i} \right)^2 \cdot u^2(x_i) \quad (4)$$

The guide recommends that the expanded uncertainty  $U(y)$ , calculated as per Eq. (5), should be described within a confidence interval which is dependent on the measurement coverage factor  $K$ . Equation (6) shows how to determine the effective degrees of freedom  $\nu_{\text{eff}}$  through the Welch-Satterthwaite equation, where  $\nu_i$  are the degrees of freedom of each input variable. The former will determine the value of  $K$  and the correspondent confidence interval.

$$U(y) = K \cdot u_c(y) \quad (5)$$

$$\nu_{\text{eff}} = \frac{u_c^4(y)}{\sum_{i=1}^N \frac{(u_i(x_i) \cdot c_{x_i})^4}{\nu_i}} \quad (6)$$

## HARDWARE AND SOFTWARE INTERFACE

Arduino® compatible hardware was chosen due to price and robustness since the measuring site is prone to contamination by dust. It consists of an ATMEGA 2560 microcontroller and a module with chip MAX31855 to read thermocouple voltage. The latter uses analogic to digital conversion with a maximum sampling rate of around 10 Hz, depending on software and hardware setup, and sends 14-bit data to SPI ports. Readings are lively shown and registered to a notebook via USB serial communication at 5 Hz in this work. The module has an inbuilt thermistor for cold junction temperature measurement that allows 0.06 °C resolution, while for thermocouples, it is 0.25 °C (Maxim Integrated, 2015). A type K thermocouple was employed, which is made from wires of Nickel-Chromium and Nickel-Aluminum alloys. Due to differences in material composition, the actual sensitivity constant might differ from the value pre-defined in the MAX31855 software library. It is a much cheaper acquisition system, all costing less than

US\$25, which is the upside against the high maximum error stated in the catalog of  $\pm 2$  °C to  $\pm 6$  °C depending on temperature interval. Although it is not adequate for precise temperature monitoring, it is enough for some less sensitive applications (Vasconcelos Neto et. al., 2018).

## UNCERTAINTY OF TEMPERATURE MEASURED BY THERMOCOUPLE AND MODULE

Equation (7) results from the application of Eq. (4) to the mathematical model of Eq. (2). The latter is linear because the variables are not correlated, and so the sensitivity coefficients resultant from the partial derivatives are all equal to 1, as shown in Eq. (8).

$$u_c^2(\Delta T) = \left( \frac{\partial \Delta T}{\partial \Delta T} \right)^2 \cdot u^2(\Delta T) + \left( \frac{\partial \Delta T}{\partial \Delta R} \right)^2 \cdot u^2(\Delta R) + \left( \frac{\partial \Delta T}{\partial \Delta \text{ICJF}} \right)^2 \cdot u^2(\Delta \text{ICJF}) + \left( \frac{\partial \Delta T}{\partial \Delta \text{IC}} \right)^2 \cdot u^2(\Delta \text{IC}) \quad (7)$$

$$c_{\Delta T} = \frac{\partial \Delta T}{\partial \Delta T} = 1; \quad c_{\Delta R} = \frac{\partial \Delta T}{\partial \Delta R} = 1; \quad c_{\Delta \text{ICJF}} = \frac{\partial \Delta T}{\partial \Delta \text{ICJF}} = 1; \quad c_{\Delta \text{IC}} = \frac{\partial \Delta T}{\partial \Delta \text{IC}} = 1 \quad (8)$$

The cold junction temperature must be verified against a calibrated instrument, such as a bulb thermometer, in a constant temperature environment. Therefore, the parcel  $\Delta \text{ICJF}$  can be calculated by applying Eq. (4) to the mathematical model of Eq. (9), where  $\Delta T_{\text{jf}}$  is the uncertainty related to cold junction temperature variability around mean,  $\Delta R_{\text{jf}}$  is the uncertainty due to the resolution of cold junction temperature measurement through the inbuilt NTC, and  $\Delta \text{ICbt}''$  comes from the calibrated bulb thermometer, which has a resolution of 0.1 °C. This yields Eq. (10) and Eq. (11).

$$\Delta \text{ICJF} = \Delta T_{\text{jf}} + \Delta R_{\text{jf}} + \Delta \text{ICbt}'' \quad (9)$$

$$u_c^2(\Delta \text{ICJF}) = \left( \frac{\Delta \text{ICJF}}{\Delta T_{\text{jf}}} \right)^2 \cdot u^2(\Delta T_{\text{jf}}) + \left( \frac{\Delta \text{ICJF}}{\Delta R_{\text{jf}}} \right)^2 \cdot u^2(\Delta R_{\text{jf}}) + \left( \frac{\Delta \text{ICJF}}{\Delta \text{ICbt}''} \right)^2 \cdot u^2(\Delta \text{ICbt}'') \quad (10)$$

$$c_{\Delta T_{\text{jf}}} = \frac{\partial \Delta \text{ICJF}}{\partial \Delta T_{\text{jf}}} = 1; \quad c_{\Delta R_{\text{jf}}} = \frac{\partial \Delta \text{ICJF}}{\partial \Delta R_{\text{jf}}} = 1; \quad c_{\Delta \text{ICbt}''} = \frac{\partial \Delta \text{ICJF}}{\partial \Delta \text{ICbt}''} = 1; \quad (11)$$

If the thermometer is not calibrated, its uncertainty can be estimated if the operator has enough knowledge of this measuring system (Vuolo, 1996), establishing a factor recommended between 0.5 to 2 to be multiplied by the resolution  $R_{\text{bt}}$  of the instrument. The broadest

factor was adopted in this work because the thermometer has not been calibrated in recent years.

## CALIBRATION OF THERMOCOUPLE AND SYSTEM

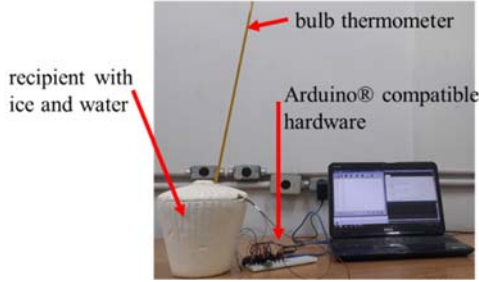


Figure 1. Calibration of thermocouple and system by fixed method point, using a mix of ice and distilled water and bulb thermometer as reference.

The calibration of thermocouples and the system can be performed by the fixed-point method, which uses phase change temperatures of substances such as distilled water. Figure 1 provides a scheme of the procedure. In order to determine  $\Delta IC$ , it is first necessary to quantify the maximum uncertainty for temperature measured in water during phase change, which is done by using the system to probe temperature at a mix of water and ice and then at boiling water. This way, the uncertainty of the measuring system is considered as the highest value obtained from applying Eq. (4) to the mathematical models of Eq. (12) and Eq. (13). This same procedure and models were carried out by Oliveira et. al. (2020). If the measurements are not performed at 20 °C and 101325 Pa, the triple point is well known; then the actual temperature must be measured by a secondary bulb thermometer, for which uncertainty will be  $\Delta ICbt$ . This results in Eq. (14) up to Eq. (17). Although this other instrument has a resolution of 0.2 °C, it is possible to use 0.1 °C through interpolation since it is analogic and has a precise scale.

$$\Delta T_{0\text{ }^{\circ}\text{C}} = \overline{\Delta T_{0\text{ }^{\circ}\text{C}}} + \Delta R + \Delta ICbt \quad (12)$$

$$\Delta T_{100\text{ }^{\circ}\text{C}} = \overline{\Delta T_{100\text{ }^{\circ}\text{C}}} + \Delta R + \Delta ICbt \quad (13)$$

$$u_c^2(\Delta T_{0\text{ }^{\circ}\text{C}}) = \left( \frac{\partial \Delta T_{0\text{ }^{\circ}\text{C}}}{\partial \overline{\Delta T_{0\text{ }^{\circ}\text{C}}}} \right)^2 \cdot u^2(\overline{\Delta T_{0\text{ }^{\circ}\text{C}}}) + \left( \frac{\partial \Delta T_{0\text{ }^{\circ}\text{C}}}{\partial \Delta R} \right)^2 \cdot u^2(\Delta R) + \left( \frac{\partial \Delta T_{0\text{ }^{\circ}\text{C}}}{\partial \Delta ICbt} \right)^2 \cdot u^2(\Delta ICbt) \quad (14)$$

$$c_{\Delta T_{0\text{ }^{\circ}\text{C}}} = \frac{\partial T_{0\text{ }^{\circ}\text{C}}}{\partial \overline{T_{0\text{ }^{\circ}\text{C}}}} = 1; \quad c_{\Delta R} = \frac{\partial T_{0\text{ }^{\circ}\text{C}}}{\partial \Delta R} = 1; \quad c_{\Delta ICbt} = \frac{\partial T_{0\text{ }^{\circ}\text{C}}}{\partial \Delta ICbt} = 1; \quad (15)$$

$$u_c^2(\Delta T_{100\text{ }^{\circ}\text{C}}) = \left( \frac{\partial \Delta T_{100\text{ }^{\circ}\text{C}}}{\partial \overline{\Delta T_{100\text{ }^{\circ}\text{C}}}} \right)^2 \cdot u^2(\overline{\Delta T_{100\text{ }^{\circ}\text{C}}}) + \left( \frac{\partial \Delta T_{100\text{ }^{\circ}\text{C}}}{\partial \Delta R} \right)^2 \cdot u^2(\Delta R) + \left( \frac{\partial \Delta T_{100\text{ }^{\circ}\text{C}}}{\partial \Delta ICbt} \right)^2 \cdot u^2(\Delta ICbt) \quad (16)$$

$$c_{\Delta T_{100\text{ }^{\circ}\text{C}}} = \frac{\partial \Delta T_{100\text{ }^{\circ}\text{C}}}{\partial \overline{\Delta T_{100\text{ }^{\circ}\text{C}}}} = 1; \quad c_{\Delta R} = \frac{\partial \Delta T_{100\text{ }^{\circ}\text{C}}}{\partial \Delta R} = 1; \quad c_{\Delta ICbt} = \frac{\partial \Delta T_{100\text{ }^{\circ}\text{C}}}{\partial \Delta ICbt} = 1; \quad (17)$$

## UNCERTAINTY OF CORRECTED TEMPERATURE

Temperature correction accounts for offset errors and discrepancies in the material sensitivity constant. It is done through linear regression of collected data, which consists only of two points. Thus, a linear equation can be simply calculated through the coordinates  $(x_0; y_0)$  and  $(x_1; y_1)$  that correspond to values obtained by thermocouple system and bulb thermometer, for which the points  $(Tbt_{0\text{ }^{\circ}\text{C}}, T_{0\text{ }^{\circ}\text{C}})$  and  $(Tbt_{100\text{ }^{\circ}\text{C}}, T_{100\text{ }^{\circ}\text{C}})$  are shown in Fig. 2.

Solving the linear system of Eq. (18) yields Eq. (19), from which the corrected temperature  $T_c$  is determined in Eq. (20) according to the temperature indicated by the measuring system. After substituting the average values for each variable, Eq. (21) is obtained. The uncertainty of  $T_c$  is determined through the application of Eq. (4) to Eq. (20), taking into consideration that uncertainty can never be subtracted, yielding Eq. (22) and Eq. (23). In this case, the partial derivatives will be different from 1, and they are determined by the average values of each variable, as shown in Eq. (24) to Eq. (26). The uncertainties  $\Delta Tbt_{0\text{ }^{\circ}\text{C}}$  and  $\Delta Tbt_{100\text{ }^{\circ}\text{C}}$  are estimated after applying Eq. (4) again, as described in Eq. (27) to Eq. (32).

$$y_0 = a \cdot x_0 + b \quad ; \quad y_1 = a \cdot x_1 + b \quad (18)$$

$$a = \frac{(y_1 - y_0)}{(x_1 - x_0)} = \frac{(Tbt_{100\text{ }^{\circ}\text{C}} - Tbt_{0\text{ }^{\circ}\text{C}})}{(T_{100\text{ }^{\circ}\text{C}} - T_{0\text{ }^{\circ}\text{C}})} \quad ; \quad b = \frac{(Tbt_{100\text{ }^{\circ}\text{C}} - a \cdot T_{100\text{ }^{\circ}\text{C}})}{(T_{100\text{ }^{\circ}\text{C}} - T_{0\text{ }^{\circ}\text{C}})} \quad (19)$$

$$T_c = \frac{(Tbt_{100\text{ }^{\circ}\text{C}} - Tbt_{0\text{ }^{\circ}\text{C}})}{(T_{100\text{ }^{\circ}\text{C}} - T_{0\text{ }^{\circ}\text{C}})} \cdot T + \frac{(Tbt_{100\text{ }^{\circ}\text{C}} - a \cdot T_{100\text{ }^{\circ}\text{C}})}{(T_{100\text{ }^{\circ}\text{C}} - T_{0\text{ }^{\circ}\text{C}})} \quad (20)$$

$$T_c = 1.01991 \cdot T - 1.30713 \quad (21)$$

$$\Delta T_c = \frac{(\Delta T_{bt_{100^\circ C}} + \Delta T_{bt_{0^\circ C}}) \cdot \Delta T}{(\Delta T_{100^\circ C} + \Delta T_{0^\circ C})} + \frac{(\Delta T_{bt_{100^\circ C}} + \Delta T_{bt_{0^\circ C}})}{(\Delta T_{100^\circ C} + \Delta T_{0^\circ C})} \cdot \Delta T_{100^\circ C} + \Delta T_{bt_{100^\circ C}} \quad (22)$$

$$u_c^2(\Delta T_c) = \left( \frac{\partial \Delta T_c}{\partial \Delta T_{bt_{100^\circ C}}} \right)^2 \cdot u^2(\Delta T_{bt_{100^\circ C}}) + \left( \frac{\partial \Delta T_c}{\partial \Delta T_{bt_{0^\circ C}}} \right)^2 \cdot u^2(\Delta T_{bt_{0^\circ C}}) + \left( \frac{\partial \Delta T_c}{\partial \Delta T_{100^\circ C}} \right)^2 \cdot u^2(\Delta T_{100^\circ C}) + \left( \frac{\partial \Delta T_c}{\partial \Delta T_{0^\circ C}} \right)^2 \cdot u^2(\Delta T_{0^\circ C}) + \left( \frac{\partial \Delta T_c}{\partial \Delta T} \right)^2 \cdot u^2(\Delta T) \quad (23)$$

$$c_{\Delta T_{bt_{100^\circ C}}} = \frac{\partial \Delta T_c}{\partial \Delta T_{bt_{100^\circ C}}} \cdot \frac{\Delta T + \Delta T_{100^\circ C}}{\Delta T_{100^\circ C} + \Delta T_{0^\circ C}} + 1; \quad c_{\Delta T_{bt_{0^\circ C}}} = \frac{\partial \Delta T_c}{\partial \Delta T_{bt_{0^\circ C}}} \cdot \frac{\Delta T + \Delta T_{100^\circ C}}{\Delta T_{100^\circ C} + \Delta T_{0^\circ C}}; \quad (24)$$

$$c_{\Delta T_{0^\circ C}} = \frac{\partial \Delta T_c}{\partial \Delta T_{0^\circ C}} \cdot \frac{(\Delta T_{bt_{100^\circ C}} + \Delta T_{bt_{0^\circ C}}) \cdot (-\Delta T - \Delta T_{100^\circ C})}{(\Delta T_{100^\circ C} + \Delta T_{0^\circ C})^2}; \quad c_{\Delta T} = \frac{\partial \Delta T_c}{\partial \Delta T} = \frac{\Delta T_{bt_{100^\circ C}} + \Delta T_{bt_{0^\circ C}}}{\Delta T_{100^\circ C} + \Delta T_{0^\circ C}}; \quad (25)$$

$$c_{\Delta T_{100^\circ C}} = \frac{\partial \Delta T_c}{\partial \Delta T_{100^\circ C}} \cdot \frac{(\Delta T_{bt_{0^\circ C}} + \Delta T_{bt_{100^\circ C}}) \cdot (\Delta T_{0^\circ C} - \Delta T)}{(\Delta T_{100^\circ C} + \Delta T_{0^\circ C})^2}; \quad (26)$$

$$\Delta T_{bt_{0^\circ C}} = \overline{\Delta T_{bt_{0^\circ C}}} + \Delta R_{bt} + \Delta IC_{bt} \quad (27)$$

$$u_c^2(\Delta T_{bt_{0^\circ C}}) = \left( \frac{\partial \Delta T_{bt_{0^\circ C}}}{\partial \overline{\Delta T_{bt_{0^\circ C}}}} \right)^2 \cdot u^2(\overline{\Delta T_{bt_{0^\circ C}}}) + \left( \frac{\partial \Delta T_{bt_{0^\circ C}}}{\partial \Delta R_{bt}} \right)^2 \cdot u^2(\Delta R_{bt}) + \left( \frac{\partial \Delta T_{bt_{0^\circ C}}}{\partial \Delta IC_{bt}} \right)^2 \cdot u^2(\Delta IC_{bt}) \quad (28)$$

$$c_{\Delta T_{bt_{0^\circ C}}} = \frac{\partial \Delta T_{bt_{0^\circ C}}}{\partial \overline{\Delta T_{bt_{0^\circ C}}}} = 1; \quad c_{\Delta R_{bt}} = \frac{\partial \Delta T_{bt_{0^\circ C}}}{\partial \Delta R_{bt}} = 1; \quad c_{\Delta IC_{bt}} = \frac{\partial \Delta T_{bt_{0^\circ C}}}{\partial \Delta IC_{bt}} = 1; \quad (29)$$

$$\Delta T_{bt_{100^\circ C}} = \overline{\Delta T_{bt_{100^\circ C}}} + \Delta R_{bt} + \Delta IC_{bt} \quad (30)$$

$$u_c^2(\Delta T_{bt_{100^\circ C}}) = \left( \frac{\partial \Delta T_{bt_{100^\circ C}}}{\partial \overline{\Delta T_{bt_{100^\circ C}}}} \right)^2 \cdot u^2(\overline{\Delta T_{bt_{100^\circ C}}}) + \left( \frac{\partial \Delta T_{bt_{100^\circ C}}}{\partial \Delta R_{bt}} \right)^2 \cdot u^2(\Delta R_{bt}) + \left( \frac{\partial \Delta T_{bt_{100^\circ C}}}{\partial \Delta IC_{bt}} \right)^2 \cdot u^2(\Delta IC_{bt}) \quad (31)$$

$$c_{\Delta T_{bt_{100^\circ C}}} = \frac{\partial \Delta T_{bt_{100^\circ C}}}{\partial \overline{\Delta T_{bt_{100^\circ C}}}} = 1; \quad c_{\Delta R_{bt}} = \frac{\partial \Delta T_{bt_{100^\circ C}}}{\partial \Delta R_{bt}} = 1; \quad c_{\Delta IC_{bt}} = \frac{\partial \Delta T_{bt_{100^\circ C}}}{\partial \Delta IC_{bt}} = 1; \quad (32)$$

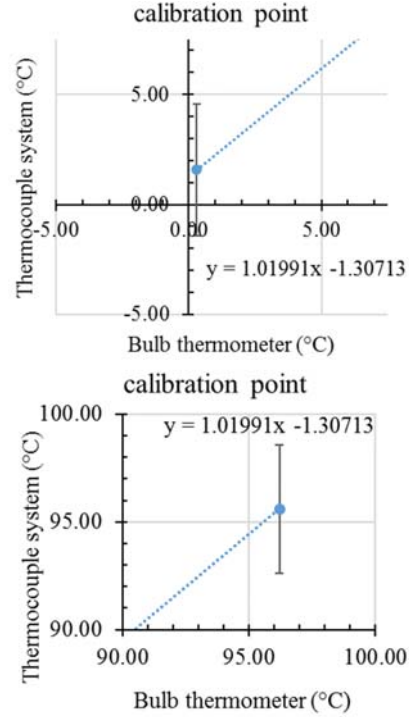


Figure 2. Temperature measurements during calibration in water mix, where bars represent the expanded uncertainty calculated for  $T_{0^\circ C}$  and  $T_{100^\circ C}$  with a 95.45 % confidence interval and 1 effective degree of freedom.

## RESULTS

Table 1 shows the data obtained with this measuring system in an industrial application for measuring temperature during deposition of coatings through directed heat. The temperature  $T$  was measured for 7 s, and the methodology was applied to calculate the correct temperature  $T_c$  based upon calibration. Degrees of freedom for type A evaluation depend on the number of points  $n$  used for calculating the mean, such that  $DOF = n - 1$ . Meanwhile, for type B evaluations, it depends on the distribution assumed for that variable. Again, the GUM (INMETRO, JCGM, 2008) shows how each parameter is determined. The number of points during calibration should be high, showing that the water phase mix is in equilibrium. Fewer points should suffice for other measurements, depending on how stable the system is.

Table 1. Mean, standard deviation, standard, and expanded uncertainty for the main variables. a) Thermometer (°C); b) Thermocouple system (°C).

	avg	std. dev.	max - min	n	v	uc	K	U
a) Tbt0	0.3	0.10	0.2	3	2	0.2160	12.71	2.75
Tbt100	96.2	0.30	0.6	3	2	0.2708	4.3	1.17
Tbt	22.3	0.42	0.6	1	-	-	-	-
T0	1.58	0.8	6	1198	1197	0.2139	13.97	2.99
T100	95.6	0.41	2.5	1198	1197	0.2130	13.97	2.98
b) Tjf	21.98	0.11	0.75	1180	1179	0.0031	-	-
T	76.79	0.38	1.5	35	34	0.3088	4.53	1.4
Tc	77.01	-	-	-	4	0.9869	2.78	2.75

Figure 3 shows the contributions of each source in the different models, from which it is clear that the variabilities around the average are the smallest sources of uncertainty for this system. The first reason is the high number of points n sampled since the standard uncertainty is inversely proportional to the root square of n for type A variables. The second is the low standard deviations, which are less than 1 °C, thanks to the many points and low spread of values shown by the difference between maximum and minimum in Tab. 1. Thus, this system is stable enough for industrial applications where variations of a few degrees are acceptable. The only exception is T<sub>0</sub> (0 °C), for which the measuring system seems more unstable. Still, it is in accordance with the maximum variability stated in the catalog for the MAX31855 module.

The graphs also indicate that the factor of 2 adopted to calculate the standard uncertainty for calibration of bulb thermometers was very conservative because this variable accounts for the highest source among all models that depend on it directly. The choice of this factor yielded greater values for the uncertainty of the measured and corrected temperature since each of the contributing factors accumulate together and increase the final uncertainty, as shown in Fig. 4. Thus, a lower factor such as 1 or 0.5 is recommended for future works.

Regarding the higher variability for the bulb thermometer at 100 °C, this can be associated with the convection currents in boiling water, which are much stronger than in melting ice. This caused the slightly higher standard uncertainty of this variable, represented by the first purple bar in Fig. 4.

Table 1 shows that the corrected temperature is very close to the normal measurement, with less than 0.5 °C of difference. Indeed, due to the linear model and the higher error obtained during calibration for 0 °C, the temperatures will be very close for temperatures near 100 °C. This is expected because the linearity of K thermocouples is about 99 % in this range (Omega Engineering, 2015). That does not mean the correction is unimportant, mainly because there is

a significant change in the standard uncertainty from T to T<sub>c</sub>, which increases more than twice. This happens due to contributions from all uncertainties related to calibration procedures, in which it is possible to see a significant contribution from  $\{T_{bt}\}_{-}(100\text{ }^{\circ}\text{C})$  due to a higher coefficient of sensitivity. This is a circumstantial consequence of the mathematical model for the linear regression since the standard uncertainty of this variable is smaller than T, for instance.

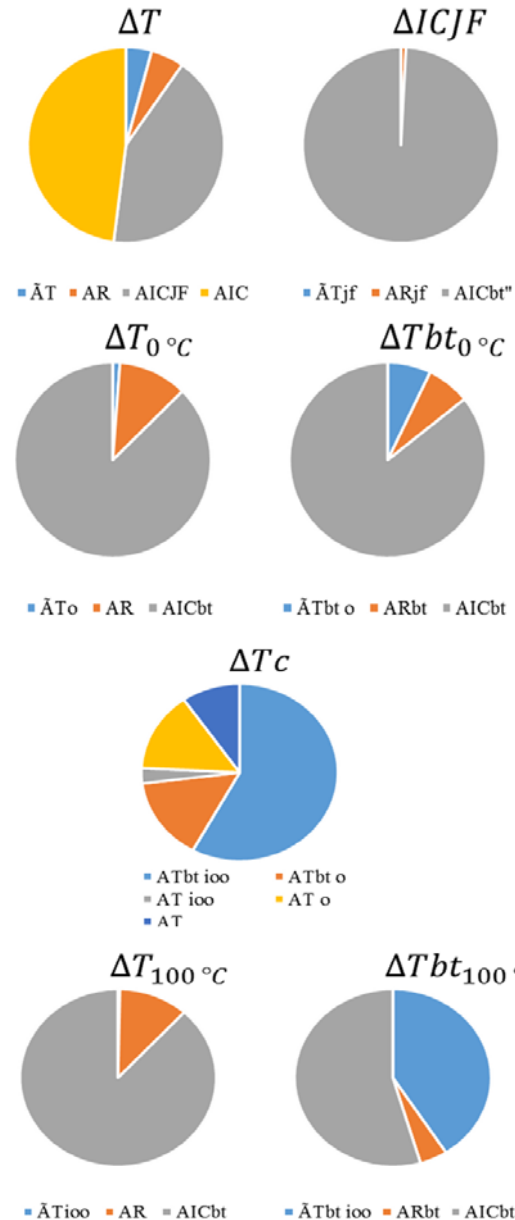


Figure 3. Percentage contribution of each source in different uncertainty models.

Finally, the measurement result can be expressed as shown in Eq. (33), in accordance with the NBR

ISO/IEC 17025:2017 (ABNT, ISO/IEC, 2017). The measurement, now fully characterized, gives a clear idea of the precision of the measuring system. As stated before, this precision is enough for applications that allow slight variations in process temperature. Although the primary examples cited were industries, this measuring system can also be safely employed in many research applications for manufacturing processes such as machining and welding. In such cases, there is often the need to analyze temperatures that differ much more than 3 °C when changing process parameters, and the measurement with Arduino® microcontroller and hardware would be much cheaper than the commonly used Agilent boards.

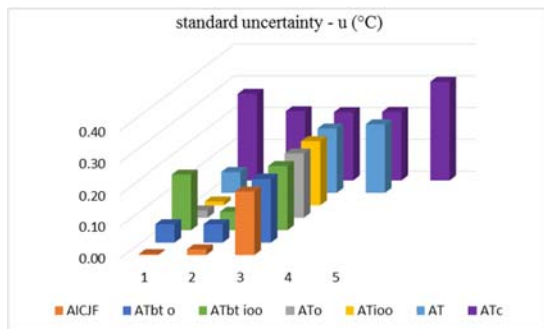


Figure 4. Absolute values for standard uncertainties relative to each source for the various models. The numbers in the x-axis refer to the parcels in each model of Fig. 3.

$$T_c = 77.01 \pm 2.75 \text{ } ^\circ\text{C with K} \quad (21)$$

= 2.78 and 95% confidence interval

## CONCLUSIONS

The procedures for uncertainty assessment are usually very time-consuming, which is the main reason why most works do not approach this domain. Nevertheless, once the methodology is *st*<UNK>, it can be easily turned into a computational routine for calculation with any similar data using software like Excel® or Matlab®. Above all, it reveals the primary sources of uncertainty, which in this case related to the calibration of the instruments. The low variability around the average indicates that a lower acquisition rate could be used without prejudice and that the temperature variations are not much more significant than the resolution of the system. Since the main application is for processes that are tolerant to slight variations, the measuring system is adequate. Also, this work shows how the different variables may interact in more complex models, such as in the calculation of  $\Delta T_c$ , for which uncertainty was much higher than before correction.

The equations described are applicable for any other measurements performed with thermocouples and other data acquisition systems in industrial and

laboratory applications. The same mathematical models may be used to estimate the uncertainty through the Monte Carlo method, although the procedure for determining each standard uncertainty is different in this second methodology. The precision of about 3 °C indicates a very cost-effective solution when comparing the US\$20 Arduino® board and module with an Agilent board that may cost a few hundred dollars, or even more, thus making it an attractive solution for research applications as well.

The final calculations give a clear idea about the precision of the whole measuring system, but it guarantees its traceability to make comparisons against other measurements conducted in the same conditions and different measuring systems. That is of utmost importance because, as discussed in the GUM (INMETRO, JCGM, 2008), there is a worldwide tendency to apply these uncertainty assessment routines in all future works to evaluate the repeatability and reproducibility of results either in industrial or in research applications.

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