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Comment on "*A low-cost cryogenic temperature measurement system using Arduino microcontroller*"

Zoltan Gingl and Robert Mingesz

Department of Technical Informatics, University of Szeged, Árpád tér 2, 6720 Szeged, Hungary

E-mail: gingl@inf.u-szeged.hu

Abstract

A recent paper (Woong Sung Lee 2020 *Phys. Educ.* **55** 023002) demonstrates how to build a low-cost Arduino-based system to measure temperature down to 77 K. The idea is interesting, and the paper has several merits, however we have found considerable mistakes. In our comment we point out what are the problems and show solutions too. We think that our analysis can help the reader to see what should be considered for proper operation and to see how the related methods can be useful concerning STEM education also. Our contribution can support reliable and accurate temperature measurement without calibration.

Analysis of the signal conditioning circuit

The technical specifications of the temperature sensor diode DT-670 used by the author say that a constant current of 10 μA±0.1% should be applied during the measurement of the forward voltage. The author aimed to follow this, but the circuit in Figure 1 of the paper [1] do not provide constant current. The main problem is that the varying voltage drop on the diode was ignored in the design. The output voltage of the LM317 is close to 1.6V (nominally 1.67 V according to the datasheet of the LM317), the 160 kΩ resistance formed by two series 80 kΩ resistors could only set 10 μA constant current, if the diode voltage would be 0 V. Therefore, the current strongly depends on the diode forward voltage, and according to this, on temperature. In the reported measurement range the current change can be more than 50%. This clearly violates the requirements and makes the temperature dependence of the sensor voltage unpredictable. Note also, that R4 is short-circuited, thus the loop has a resistance value of 80 kΩ instead of 160 kΩ. It is even more strange to see in Figure 3, that the anode of the diode is floating, it is not connected to R3. The wire is plugged into the empty row labelled by 10 of the breadboard, while the terminal of R3 is placed in row 9, therefore it cannot be the photo of the working version.

The author suggests that the DT-670 diode can be replaced by any glass encapsulated diode, e.g. 1N914. However, the absolute maximum ratings of the 1N914 diode manufactured by ON Semiconductor specifies the storage temperature range from -65°C to 200°C and the operating junction temperature range from -55°C to 175°C. One should never use devices out of such specifications [2], to emphasize this, the following warning can be read in the datasheet: '*Stresses exceeding those listed in the Maximum Ratings table may damage the device. If any of these limits are exceeded, device functionality should not be assumed, damage may occur and reliability may be affected.*'. The DT-670 costs more than $200, it cannot be replaced by a sub-$1 diode.

The Arduino A/D converter's voltage reference was an USB port's 5 V supply voltage. This voltage is inaccurate, can fluctuate, can vary from port to port, therefore using it is not recommended in an analogue application, especially for demanding measurements [3]. The resolution is 5 V/1024, close to 5 mV. This corresponds to a temperature resolution of about 2.4 K, if we take the average sensitivity of 2.1 mV/K of the DT-670 diode.

According to the above, it is hard to believe that a maximum of 2 K error can be expected from this system, the observation could only be accidental, we think. This error is even less than the resolution of the measurement, significantly smaller than the error specification of the A/D converter of the microcontroller [3] and the varying current is far from what is required for proper sensor biasing.

About calibration

Calibration can reduce errors, but only if the reference values are known with higher accuracy than what the system can provide by default. The two-point calibration in combination with linear approximation applied in the work [1] cannot deal with the inherent non-linearity of the DT-670 sensor. For example, it is specified to exhibit forward voltage of 1.031651 V at 75 K, 0.559639 V at 300 K. Therefore, linear approximation gives 193.2 K at 0.78372 V, while the specifications assigns 200 K to this forward voltage. Thus, the linear approximation can introduce an error close to 7 K at this temperature. This is another reason why it is so surprising to observe maximum error close to 2 K.

However, if the sensor is operated in such conditions what is required according to the datasheet, and the specified sensor characteristics are used to convert the forward voltage to temperature, then one can obtain good accuracy even without calibration. This is a real advantage, since calibration needs expertise, costly instruments, very carefully prepared conditions [3]. The inherently high accuracy of the DT-670 sensor will be degraded very likely if the unnecessary calibration procedure mentioned in the paper is executed.

Accurate sensor signal conditioning

Accurate sensor signal monitoring systems can be built using an Arduino board, indeed [4]. Figure 1 shows a precise signal conditioning circuitry to allow the DT-670 sensor to be used in an Arduino UNO based measurement.

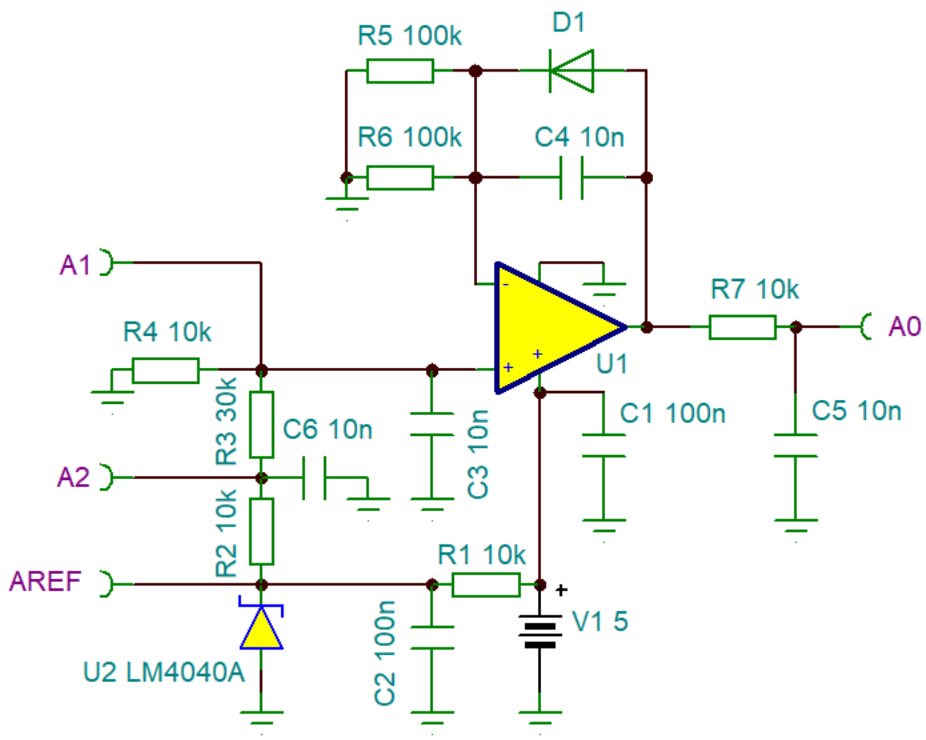

Figure 1. Signal conditioning circuit to pass accurate constant current through the D1 sensor diode and to support Arduino UNO based measurement. The A0, A1, A2 and AREF terminals and the two terminals of V1 (5 V and ground) represent the Arduino UNO pin connections. Resistors R2 trough R6 should have tolerance of 0.1%. The components except the sensor cost about $5.

The 5 V supply from the Arduino board is represented by V1. Keep in mind that powering from an USB port should be avoided in a more demanding application [3]. U2 is a precise voltage reference, LM4040A, with output voltage of 2.5 V±0.1% at room temperature. Its bias current is set by R1. The 0.1% tolerance resistors R2, R3 and R4 form a voltage divider with two accurate outputs, 0.5 V and 2 V at terminals A1 and A2, respectively. At the non-inverting input of the single supply operational amplifier (U1) the voltage is 0.5 V, therefore the same value voltage appears at the inverting input. Thus, the voltage drops on the R5 and R6 resistors, whose tolerance should be 0.1%, are 0.5 V, so their currents are set to 5 µA. The 10 µA sum of these currents flows through the diode. The operational amplifier should have offset voltage less than 0.5 mV and input current below 10 nA to maintain the 0.1% accuracy (for example, the OPA333 or MCP6021-E/P is sufficient). The output voltage at A0 is 0.5 V+V_f, where the diode forward voltage V_f falls in the range from 0.09 V to 1.65 V if the full temperature range (1.4 K to 500 K) is considered. The accurate 2.5 V reference voltage used also as the reference AREF of the microcontroller's A/D converter. Be sure to program the microcontroller to use the external reference before connecting it to the AREF input, otherwise a dangerous short circuit can be created with other reference sources. The resolution is 2.5 V/1024, accordingly the temperature resolution is close to 1 K. The diode forward voltage can be obtained as the difference of the voltages measured at the A0 and A1 terminals. In addition, the accurate voltages at the A1 and A2 pins can be used to remove both the offset and gain errors of the A/D converter automatically.

The datasheet provides a lookup table for the diode forward voltage temperature dependence, what can be easily used in the Arduino code. The basic version of the DT-670 sensor is specified to have accuracy of 1 K, the presented circuit plus the A/D converter add no more than 2 K uncertainty, so the overall temperature error can be kept below 3 K without calibration. This is more than enough for educational purposes and can be reliably reproduced.

Acknowledgments

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