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Investigation of a thermistor temperature measurement system with sub millikelvin resolution

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Abstract

Thermal issues in precision machine tools are the main cause for geometrical errors of workpieces. For this reason, temperature control, air and fluid conditioning and compensation techniques are often used to reduce the influence of heat sources and sinks and the associated heat transfer. This paper shows the characterization of a thermistor temperature measurement system. The system is based on the principle of ratiometric measurement using an excitation current source, analog lowpass filters and a 24 bit Delta-Sigma-AD-converter. To minimize errors due to the Seebeck effect, a method for reversing the excitation current is implemented. The circuit board has three channels to evaluate thermistors. The data interface is based on ethernet using either UDP or the MQTT-protocol. A power-over-Ethernet module is used as power source. The investigations show the 1st order time constant, the possible maximum resolution, the linearity and the advantage of excitation current reversal. The time constant is determined by the step response of the system. A solid-state calibrator block and a calibrated reference thermometer are used to estimate the resolution. This setup is also used to observe the linearity of the system in the measurement range from 15 °C to 25 °C. The work also shows the effect of the inversion of the excitation current.

Thermistor thermometry; High resolution thermometry; Thermistor; RTD; Ratiometric measurement; Sub milli Kelvin resolution; Ethernet based data interface; UDP based data interface; NTC

1. Introduction

To further improve the current temperature control, air and fluid conditioning and compensation techniques in precision machine tools it becomes necessary to use sensors with higher resolution. Currently available sensors for industrial applications have a maximum resolution of about ten millikelvin. This paper proposes a sensor with a resolution of less than one millikelvin and a measurement range of fifteen to twenty-five degrees Celsius for industrial applications.

There is already some promising work in this area, but due to some limitations it is not exactly applicable to this case.

Benjaminson and Hammond [11] developed a high resolution themperature sensor using a quartz oscillator made from a specially cut quartz with a high temperature coefficient. With such a device, the maximum possible resolution is proportional to the sampling time. A higher sampling time results in a higher resolution [10, 12, 13, 14, 17]. According to their work, to achieve a resolution of one millikelvin, a sampling time of one second would have to be selected. For industrial applications, this principle is only applicable to a limited extent, since the cycle times of real-time processors are usually much higher.

Wudy et al. [2] showed that it is possible to achieve high resolution for temperature sensors with a thermistor in a simple voltage divider circuit combined with analog low pass filters and high resolution analog to digital converters (ADC's) The main advantage of this system is the simple design of the circuit. With the developed system, a maximum resolution of seventy-five microkelvin was achieved. The main disadvantage of this circuit is its susceptibility to interference from the voltage source and the maximum sampling rate of ten Hertz, which is somewhat low for use in industrial control systems.

Higuchi et al. [3] used a similar concept, but the thermistor is measured in a Wheatstone bridge, instead of a voltage divider and is also filtered with analog low-pass filters. This setup has similar disadvantages with regard to the interference of the voltage source and the low sampling rate of one hertz.

There is also an integrated circuit (IC) LTC2983 from Linear Technology [1] available, specifically designed for high-resolution ratiometric resistance measurements. This IC implements excitation current reversal and contains two precise excitation current sources. The IC is also capable of storing six Steinhart-Hart parameters, which provide a good approximation of the thermistor's non-linear behaviour [14]. With a maximum sampling rate of six hertz, this IC is also somewhat slow for industrial use [10] .

2. Description of the developed sensor

The sensors setup can be seen in Figure 1. The sensor basically consists of three parts. The POE-part consists of a classic power over ethernet design, using full bridge rectifier (B1), flyback-dc-dc- converter (B2) and a output-lowpass filter (B3) [4, 5, 6, 7, 8].

The digital-part is formed by an 8-bit microcontroller for the ethernet-communication and the calculation of the temperature values (B7), as well as a 24 bit ADC for the thermistor measurement (B8), which also consists of two excitation current sources.

The analog part consists of a low pass filter circuit (B9), a transistor circuit (B10) for the inversion of the excitation current and the two resistors R_{ref} for the reference and R_T for the thermistor.

The thermistor was chosen because of its high sensitivity. This is considerably higher than that of platinum resistors, for example [15].

In the real setup, up to three thermistors can be connected to the transistor circuit, which can be individually selected by the microcontroller.

The thermistors are measured using the ratiometric measurement principle. This means that the measurement result is independent of the excitation current source so that disturbances of the excitation current won't have effects on the measurement result. [1]

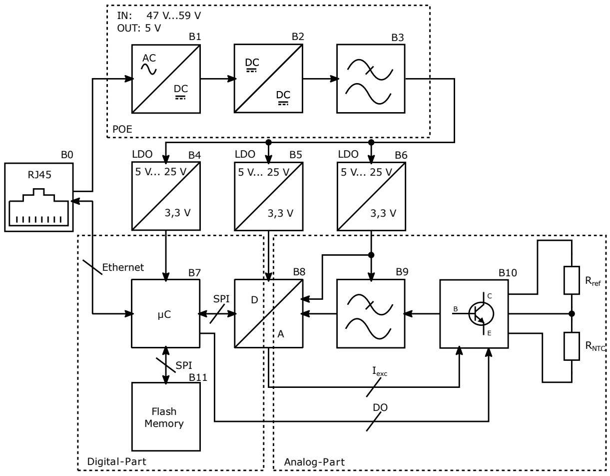

Figure 1. Block diagram of the developed sensor [5]

The following basic voltage divider equation can be used to calculate the resistance of the thermistor from the ADC readings. Here U_{T} is the Voltage across the thermistor, U_{ref} is the Voltage across the reference resistor and R_{ref} is the constant reference resistance.

$$R_{\mathrm{T}} = \frac{U_{\mathrm{T}}}{U_{\mathrm{ref}}} \cdot R_{\mathrm{ref}} \qquad 1$$

To obtain an accurate measurement result an ADC capable of sampling two differential input channels simultaneously is used. [1]

The temperature value is calculated from the resistance of the thermistor using the Steinhart-Hart equation [14, 16]. Six parameters were used for the developed sensor. This proved to be sufficient during development. A significant advantage of using the Steihnhart-Hart equation is that the curve can be approximated to the sensor characteristic by any number of measured reference values in the desired measuring range.

Furthermore, this can be done individually for each sensor element, which reduces errors due to component scattering.

During the development of the sensor, the parameters were calculated by linear regression [14] using the seventy-two measurement points given in the data sheet [20].

The developed sensor is POE-compatible according to the IEEE802.3af standard (class 3). This means that a single RJ45 socket (B0) is sufficient to connect the sensor to a PC or PLC and simultaneously supply it with power. The power can be transmitted via the two data pairs as well as via the two spare pairs of the Ethernet cable. The maximum available power is 12.95 W, which is quite sufficient for this device [4, 5, 6, 7, 8]. Theoretically, all Ethernet-based protocols can then be implemented. In this case, MQTT and UDP were used [18].

3. Determination of the maximum resolution

The maximum resolution of an ADC is limited by its noise. [2] A suitable measure for assessing the signal quality of a system is the signal-to-noise ratio (SNR). [9]

3.1. Measurement of the signal to noise ratio

For this purpose a resistor with a low temperature coefficient is placed in the circuit instead of the thermistor. The entire measurement is performed in a temperature-controlled room in order to keep influences caused by temperature fluctuations as low as possible. The sampling frequency for this and the other measurements is eighty hertz.

In general the SNR can be calculated from the mean value of the voltage of a dataset and the corresponding standard deviation.

Using Ohms law, the SNR can be calculated from the mean value of the resistance R_{eff} and the corresponding standard deviation σ_R as follows.

$$SNR = \frac{{R_{\mathrm{eff}}}^2}{{\sigma_R}^2} \qquad 2$$

3.2. Measurement result of the signal to noise ratio

The result of the SNR – measurement is shown in table 1. Figure 2 shows the corresponding histogram of the conducted measurement.

Table 1 Result of the SNR – measurement. The number of samples (NoS) used for the measurement is given in the right column.

R_{eff} / $k\Omega$	σ_R / Ω	SNR	NoS
13.696	0.0108	$1.61 \cdot 10^{12}$	126830

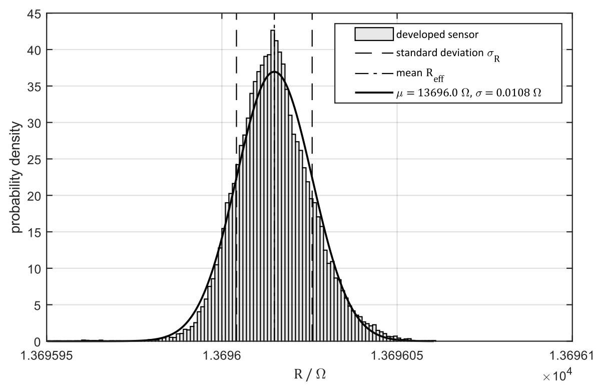

Figure 2. Histogram of the measurement for the SNR with a fitted gaussian curve with the corresponding mean and standard deviation.

The thermistor used in the setup has a sensitivity S_{R} of $512.30\ \frac{\Omega}{K}$. Using the standard deviation of table 1, equation 3 calculates a maximum resolution of $\Delta T_{\max} = 0.0211$ mK.

The results of this measurement and especially equiation 3 show that the SNR of the analog circuit, combined with the ADC and the sensitivity of the used sensor element are the limiting factors, when it comes to increasing the resolution of sensors of this type.

$$\Delta T_{\max} = \frac{\sigma_{\mathrm{R}}}{S_{\mathrm{R}}} \qquad 3$$

4. Time constant

The first order time constant was estimated from the step response of the sensor. Therefore the sensor was immersed in water with a temperature different from room temperature. The time was then measured from the point where the sensor touched the water until the temperature reached sixtythree percent of the temperature step.

The result for the time constant τ_{63} is 2.9 seconds.

5. Excitation current reversal

To reduce errors due to the Seebeck effect or other parasitic offsets in the circuit, the excitation current can be reversed [1]. The result of this method is shown in Figure 3. There is a large offset between the measurements with opposite current direction. This shows that it is possible to calibrate out offset errors by reversing the excitation current. Due to the fact that the offset error remains constant over the whole measurement period of about fourty minutes, it seems sufficient to repeat the excitation current reversal calibration in larger timesteps of several hours.

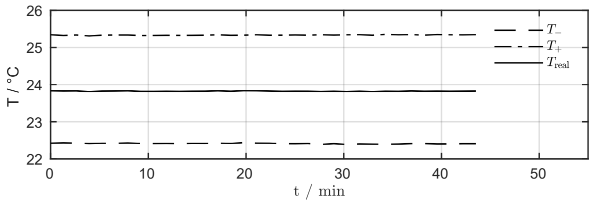

Figure 3. Excitation current reversal, T- means negative, T+ positive current direction [5].

6. Linearity

A solid-state calibrator block is used to determine the linearity of the system. This is an aluminium block in which the sensor can be placed together with a reference device. Due to the high thermal conductivity of aluminium, both sensors then have approximately the same ambient temperature.

Both sensors are then used to record the temperature over several hours. Due to the small measurement range the change in room temperature over a day was sufficient.

To avoid high measurement offsets between both sensors, the developed sensor is calibrated before, using a simple offset calibration and also the excitation current reversal method.

As a measure of linearity the correlation coefficient can be calculated out of the measurement data of the two sensors.

6.1. Measurement result of the linearity measurement

The result in Figure 4 shows that both series of measurement data are quite similar to each other. However the reference sensor seems to have a smoother response to temperature changes, which is assumed to be caused by a higher time constant of the reference sensor.

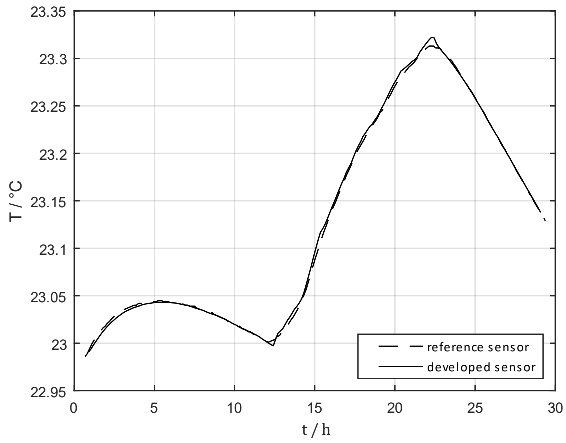

Figure 4. Comparison between the developed (black) and the reference sensor (gray).

Figure 5 shows the correlation between the reference sensor and the developed sensor. It can be said, that there is good correlation between both of them. The calculated correlation coefficient is $R_{\mathrm{Corr}} = 0.99978$, so that a high linearity of the developed sensor can be assumed.

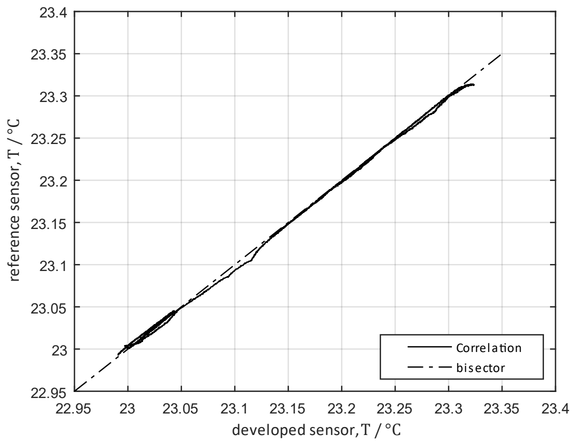

Figure 5. Diagram of the correlation between the reference sensor (Y) and the developed sensor (X)

7. Conclusion

The developed sensor shows that it is possible to develop temperaturesensors with a sub-millikelvin resolution and good linearity for industrial applications on relatively low costs.

The measurements carried out show that with a combination of using the Steinhart-Hart equation, reversing the excitation current and calibrating in the solid-state calibrator block, good calibration results can be achieved without using expensive equipment such as tripple-point cells.

The Ethernet interface wit POE makes the sensor easy to use and reduces the wiring effort in industrial use cases.

The MQTT protocol is well suited for the data transfer of the measurement data since the different measuring channels can be well divided into individual topics here.

It should be noted, that these protocols are non-real-time protocols. This can lead to unsteady delays between sending and receiving the measured values.

For the further development of this sensor, the use of real-time capable protocols such as Profinet, Profibus or IO-Link should therefore be considered [18, 19].

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